

# Transfer of Siegel cusp forms of degree 2

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**ABSTRACT.** Using Furusawa’s integral representation for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$  combined with a pullback formula involving a unitary group  $\mathrm{GU}(3, 3)$ , we prove that the  $L$ -functions  $L(s, \pi \times \tau)$  are “nice”, where  $\pi$  is the automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$  generated by a full level cuspidal Siegel eigenform that is not a Saito-Kurokawa lift, and  $\tau$  is an arbitrary cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$ . The converse theorem of Cogdell and Piatetski-Shapiro then implies that such representations  $\pi$  have a functorial lifting to a cuspidal representation of  $\mathrm{GL}_4(\mathbb{A})$ . Combined with the exterior-square lifting of Kim, this also leads to a functorial lifting of  $\pi$  to a cuspidal representation of  $\mathrm{GL}_5(\mathbb{A})$ . As an application, we obtain analytic properties of various  $L$ -functions related to full level Siegel cusp forms. We also obtain special value results for  $\mathrm{GSp}_4 \times \mathrm{GL}_1$  and  $\mathrm{GSp}_4 \times \mathrm{GL}_2$ .

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MSC: 11F70, 11F46, 11F67

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## Introduction

Let  $F$  be a Siegel cusp form of degree 2 and weight  $l$  with respect to the full modular group  $\mathrm{Sp}_4(\mathbb{Z})$ . Assuming that  $F$  is an eigenform for all Hecke operators, let  $\pi$  be the automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$  generated by (the adelization of)  $F$ . In this paper we study the tensor product  $L$ -function  $L(s, \pi \times \tau)$ , where  $\tau$  is an arbitrary cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$ . Via an integral representation pioneered by Furusawa [15], we show that this  $\mathrm{GSp}_4 \times \mathrm{GL}_2$   $L$ -function is “nice”, provided  $F$  is not of Saito-Kurokawa type. Here, niceness means that  $L(s, \pi \times \tau)$  has analytic continuation to an entire function, is bounded in vertical strips, and satisfies the expected functional equation.

As is well known, niceness of twists of  $L$ -functions can lead to liftings of automorphic forms to  $\mathrm{GL}_n$  via the converse theorem. Indeed, in combination with known results for  $L(s, \pi \times \chi)$ , where  $\chi$  is a Hecke character, our results imply a strong lifting of  $\pi$  to a cuspidal, automorphic representation of  $\mathrm{GL}_4(\mathbb{A})$  via the converse theorem of [10]. Note that the representation  $\pi$  is non-generic, since its archimedean component is a non-generic holomorphic discrete series representation. To the best of our knowledge, the converse theorem has not been used before to prove functorial transfer for a non-generic representation on a quasi-split group.

Utilizing the exterior square lifting from  $\mathrm{GL}_4$  to  $\mathrm{GL}_6$  (see [29]), we further obtain a strong lifting of  $\pi$  to  $\mathrm{GL}_5$  with respect to the 5-dimensional irreducible representation of the dual group. As an application, we prove the expected analytic properties for a host of  $L$ -functions attached to Siegel modular forms. For example, we obtain the niceness of  $L(s, \pi \times \tau)$ , where  $\tau$  is a cuspidal automorphic representation of  $\mathrm{GL}_n(\mathbb{A})$ , for *any*  $n$ ; see Theorem 5.2.2 for the precise statement. We also obtain special value results in the spirit of Deligne’s conjecture for  $L(s, \pi \times \tau)$ , where  $\tau$  is either a Hecke character of finite order or a cuspidal automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  coming from a holomorphic newform of the same weight as  $F$ . It is worth noting that the  $\mathrm{GSp}_4 \times \mathrm{GL}_2$  special value result follows directly from the integral representation and does not make use of the liftings to  $\mathrm{GL}_4$  or  $\mathrm{GL}_5$ .

Our method is based on an integral representation of Furusawa involving an Eisenstein series on a unitary group  $\mathrm{GU}(2, 2)$ ; see [15]. If  $H$  denotes the group  $\mathrm{GSp}_4$  and  $Z_H$  its center, then Furusawa considers integrals of the form

$$Z(s, f, \phi) = \int_{H(\mathbb{Q})Z_H(\mathbb{A}) \backslash H(\mathbb{A})} E(h, s; f)\phi(h) dh. \quad (1)$$

Here,  $\phi$  is a certain vector in the space of  $\pi$ , and  $E(h, s; f)$  is an Eisenstein series on  $\mathrm{GU}(2, 2)$  constructed from a section  $f$  in a globally induced representation. The quadratic extension  $L/\mathbb{Q}$  defining the group  $\mathrm{GU}(2, 2)$  is related to a global Bessel model for the representation  $\pi$ . Furusawa’s “basic identity” (here equation (132)) shows that, under suitable conditions, the integral  $Z(s, f, \phi)$

is Eulerian, i.e., it factors into a product of local zeta integrals. Furusawa has calculated the local integrals for unramified data and shown that they equal

$$\frac{L(3s + \frac{1}{2}, \tilde{\pi}_p \times \tilde{\tau}_p)}{L(6s + 1, \chi_p|_{\mathbb{Q}_p^\times}) L(3s + 1, \tau_p \times \mathcal{AI}(\Lambda_p) \times \chi_p|_{\mathbb{Q}_p^\times})},$$

where  $\chi_p$  and  $\Lambda_p$  are the local components of certain Hecke characters  $\chi$  and  $\Lambda$  of the quadratic extension. The symbol  $\mathcal{AI}$  denotes automorphic induction; thus, the second  $L$ -factor in the denominator is a factor for  $\mathrm{GL}_2 \times \mathrm{GL}_2$ . Consequently, since the  $L$ -functions in the denominator are well-understood, the integral (1) can be used to study  $L(s, \pi \times \tau)$ .

Furusawa has also calculated the archimedean local zeta integrals provided that  $\tau_\infty$  is a discrete series representation of the same weight as  $\pi_\infty$ . Hence, in the case that  $\tau$  is related to a cusp form for  $\mathrm{SL}_2(\mathbb{Z})$  of the same weight as  $F$ , the integral (1) represents the completed  $\mathrm{GSp}_4 \times \mathrm{GL}_2$   $L$ -function, divided by other  $L$ -functions which can be controlled. Furusawa used this to obtain the functional equation, as well as an algebraicity result for a special value of  $L(s, \pi \times \tau)$ .

Let us comment on the Eisenstein series  $E(h, s; f)$  appearing in (1). The underlying global induced representation is induced from the Klingen parabolic subgroup  $P$  of  $\mathrm{GU}(2, 2)$ , i.e., the maximal parabolic subgroup with non-abelian radical. The Levi component of  $P$  is such that  $P(\mathbb{A}) \cong \mathbb{A}_L^\times \times \mathrm{GU}(1, 1)(\mathbb{A})$ . The group  $\mathrm{GU}(1, 1)(\mathbb{A})$  is closely related to  $\mathrm{GL}_2(\mathbb{A})$ . In fact, via a suitably chosen Hecke character  $\chi_0$  of  $\mathbb{A}_L^\times$ , the  $\mathrm{GL}_2$  cuspidal representation  $\tau$  can be extended to a cuspidal, automorphic representation of  $\mathrm{GU}(1, 1)(\mathbb{A})$ . Together with another Hecke character  $\chi$  this defines a representation of the Levi component of  $P(\mathbb{A})$ . Parabolic induction to all of  $\mathrm{GU}(2, 2)(\mathbb{A})$  then yields representations  $I(s, \chi, \chi_0, \tau)$ , where  $s$  is a complex parameter (see Sect. 1.1 for details). The Eisenstein series is constructed from a section  $f$  in this family of induced representations. We note that, essentially,  $f$  depends on  $\tau$  alone; the  $\mathrm{GSp}_4$  representation  $\pi$  plays no role in the construction of the Eisenstein series except for the weight  $l$  which enters into the definition at the archimedean place.

Furusawa's method depends on the existence of a suitable global Bessel model for the  $\mathrm{GSp}_4$  representation  $\pi$ . If  $\pi$  is generated by a Siegel modular form  $F$ , such a Bessel model exists if and only if certain Fourier coefficients of  $F$  are non-vanishing; see Lemma 5.1.1. Using analytic methods and half-integral weight modular forms, the second author has recently proved [51] that this non-vanishing condition is always satisfied. This removes assumption (0.1) of [15], and makes our results hold unconditionally for all cuspidal Siegel eigenforms of full level.

As mentioned above, Furusawa has treated the case where the  $\mathrm{GL}_2$  representation  $\tau = \otimes \tau_v$  is unramified at every finite place, and is holomorphic of the same weight as  $\pi$  at infinity. In contrast, for our application to the converse theorem we have to allow twists by much more general  $\tau$ , including arbitrary archimedean components. This leads to considerable technical difficulties, in particular with respect to the correct choice of local sections in the local induced representations  $I(s, \chi_v, \chi_{0,v}, \tau_v)$  that enter into the definition of the global Eisenstein series. These difficulties, however, can all be overcome; we will identify distinguished vectors in all local archimedean and non-archimedean representations. In the non-archimedean case this amounts to a local newform theory for the induced representations  $I(s, \chi_v, \chi_{0,v}, \tau_v)$ ; see Sect. 1.2.

Having defined all the local sections (i.e., the Eisenstein series  $E(h, s; f)$ ) appropriately, we obtain

a global integral representation for the  $L$ -function  $L(s, \pi \times \tau)$  for *any* cuspidal, automorphic representation  $\tau$  of  $\mathrm{GL}_2(\mathbb{A})$ . This immediately yields the meromorphic continuation of the  $L$ -function  $L(s, \pi \times \tau)$  via the corresponding property of the Eisenstein series; see Sect. 2.3 for a more detailed overview of Furusawa's method. We will also obtain the desired functional equation, not however without difficult calculations of local intertwining operators; see Sect. 1.4 for the non-archimedean case, Sect. 1.5 for the archimedean case, and Sect. 2.4 for the proof of the global functional equation. Note that we obtain the functional equation only under a mild hypothesis on  $\tau$ , which however will be removed later in Theorem 5.2.2.

The holomorphy of  $L(s, \pi \times \tau)$  is more difficult to obtain. The reason is that the analytic properties of the Klingen Eisenstein series  $E(h, s; f)$  are not known to the required extent. Instead we will employ a pullback formula similar to the one in [50]. This formula expresses  $E(h, s; f)$  as an integral of a  $\mathrm{GL}_2$  automorphic form against a restricted Eisenstein series  $E_\Upsilon(g, s)$  on the larger group  $\mathrm{GU}(3, 3)$ ; see Theorem 3.5.1. This results in a second global integral representation for  $L(s, \pi \times \tau)$  involving  $E_\Upsilon(g, s)$ ; see Theorem 3.6.1. Since  $E_\Upsilon(g, s)$  is a Siegel type Eisenstein series, its analytic properties are better understood. In fact, from this second integral representation we will be able to prove the desired holomorphy of  $L(s, \pi \times \tau)$  in Theorem 4.1.1.

The definition of the  $\mathrm{GU}(3, 3)$  Eisenstein series  $E_\Upsilon(g, s)$  is not straightforward, however, and once again requires a delicate choice of local sections at all archimedean and non-archimedean places. See Sect. 3.1 for the definition in the non-archimedean case(s) and Sect. 3.3 for the definition in the archimedean case. The mechanism of the global pullback formula comes down to the evaluation of certain local zeta integrals, which we calculate in Sect. 3.2 (non-archimedean case) and Sect. 3.4 (archimedean case). After all these local preparations, we prove the global pullback formula in Theorem 3.5.1. The resulting second global integral representation is Theorem 3.6.1.

The basic analytic properties of the  $\mathrm{GU}(3, 3)$  Eisenstein series  $E_\Upsilon(g, s)$  appearing in the second global integral representation are known by the work of Tan [60]. This allows for only one possible pole of  $L(s, \pi \times \tau)$  in  $\mathrm{Re}(s) \geq 1/2$ , namely at the point  $s = 1$  (Proposition 4.1.4). The proof of holomorphy at this point requires additional arguments. We employ the regularized Siegel-Weil formula due to Ichino [26] to show that if  $L(s, \pi \times \tau)$  has a pole, then the integral of the (adelized) Siegel modular form  $F$  against a regularized theta integral is non-zero (Proposition 4.3.2). A seesaw argument then shows that  $\pi_1$ , the cuspidal, automorphic representation of  $\mathrm{Sp}_4(\mathbb{A})$  generated by  $F$ , participates in the theta correspondence with a split orthogonal group  $\mathrm{O}(2, 2)$ . But this is impossible by explicit knowledge of the archimedean local theta correspondence [47]. We thus obtain Theorem 4.1.1, which states that  $L(s, \pi \times \tau)$  is an entire function.

With the integral representation and analytic properties of  $L(s, \pi \times \tau)$  at hand, we turn to applications. The first of these is the functorial transfer of  $\pi$  to a cuspidal automorphic representation  $\Pi_4$  on  $\mathrm{GL}_4(\mathbb{A})$  via the converse theorem; see Theorem 5.1.2. Applying a backwards lifting to  $\mathrm{SO}_5(\mathbb{A}) \cong \mathrm{PGSp}_4(\mathbb{A})$ , we prove in Theorem 5.1.4 the existence of a globally generic representation on  $\mathrm{GSp}_4(\mathbb{A})$  in the same  $L$ -packet as  $\pi$ . Furthermore, the exterior square lifting from  $\mathrm{GL}_4$  to  $\mathrm{GL}_6$  established in [29] leads to a functorial transfer of  $\pi$  to a cuspidal automorphic representation  $\Pi_5$  on  $\mathrm{GL}_5(\mathbb{A})$ ; see Theorem 5.1.5.

Once the liftings are established, the machinery of Rankin-Selberg  $L$ -functions on  $\mathrm{GL}_n \times \mathrm{GL}_m$  is available for the study of  $L$ -functions related to Siegel modular forms. This is exploited in Sect.

5.2. We obtain the niceness of  $L$ -functions for  $\mathrm{GSp}_4 \times \mathrm{GL}_n$  for any  $n$ , and for  $\mathrm{GSp}_4 \times \mathrm{GSp}_4$ ; here, on the  $\mathrm{GSp}_4$ -factors, we can have the 4-dimensional or the 5-dimensional representation of the dual group. We also obtain niceness for the adjoint  $L$ -function of Siegel modular forms, as well as some analytic properties for the degree 14 and the degree 16  $L$ -functions. For the precise results, see Theorems 5.2.1, 5.2.2 and 5.2.3.

By combining our lifting results with the results of [37], we prove non-negativity at  $s = 1/2$  for the spin and the “spin  $\times$  standard”  $L$ -function as well as for suitable  $L$ -functions on  $\mathrm{GSp}_4 \times \mathrm{GL}_2$  and  $\mathrm{GSp}_4 \times \mathrm{GL}_3$ ; see Theorem 5.2.4 for the precise statement.

We also obtain critical value results in the spirit of Deligne’s conjecture for  $\mathrm{GSp}_4 \times \mathrm{GL}_1$  (Theorem 5.3.3) and for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$  (Theorem 5.3.7). Theorem 5.3.3 follows by combining our lifting theorem with a critical value result for  $\mathrm{GL}_4 \times \mathrm{GL}_1$  proved by Grobner and Raghuram [23]. Theorem 5.3.7, on the other hand, follows directly from the second global integral representation (Theorem 3.6.1) using the methods of [50].

As for related works, the transfer from  $\mathrm{GSp}_4$  to  $\mathrm{GL}_4$  for *all* cuspidal, automorphic representations should eventually follow from the trace formula. At the time of this writing, we do not know whether all the necessary elements for this far reaching program of Arthur’s have been completed. The existence of a globally generic representation of  $\mathrm{GSp}_4(\mathbb{A})$  in the same  $L$ -packet as  $\pi$  (Theorem 5.1.4) is also proved in [64] using theta liftings and the topological trace formula. We believe, however, that our present work is of independent interest, both because it provides a “proof of concept” that certain cases of non-generic transfer can be established without resorting to trace formula arguments, and because the explicit nature of our integral representation makes it a useful tool to attack other problems related to Siegel cusp forms. As an example of the latter, we would like to mention Gross-Prasad type questions for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$  as a potential future application.

We would like to thank Paul-Olivier Dehaye, Mark McKee and Paul Nelson for their help with various parts of this paper. We would also like to thank the FIM and Emmanuel Kowalski at ETH for providing an excellent working environment for us during the final phase in which this paper was written.

## Notation

### Basic objects

- i) The symbols  $\mathbb{Z}$ ,  $\mathbb{Z}_{\geq 0}$ ,  $\mathbb{Q}$ ,  $\mathbb{R}$ ,  $\mathbb{C}$ ,  $\mathbb{Z}_p$  and  $\mathbb{Q}_p$  have the usual meanings. The symbol  $\mathbb{A}_F$  denotes the ring of adeles of an algebraic number field  $F$ , and  $\mathbb{A}_F^\times$  denotes its group of ideles. The symbols  $\mathbb{A}$  and  $\mathbb{A}^\times$  will always denote  $\mathbb{A}_\mathbb{Q}$  and  $\mathbb{A}_\mathbb{Q}^\times$  respectively.
- ii) For any commutative ring  $R$  and positive integer  $n$ , let  $\mathrm{Mat}_{n,n}(R)$  denote the ring of  $n \times n$  matrices with entries in  $R$ , and let  $\mathrm{GL}_n(R)$  denote the group of invertible elements in  $\mathrm{Mat}_{n,n}(R)$ . We use  $R^\times$  to denote  $\mathrm{GL}_1(R)$ . If  $A \in \mathrm{Mat}_{n,n}(R)$ , we let  ${}^t A$  denote its transpose.
- iii) Define  $J_n \in \mathrm{Mat}_{n,n}(\mathbb{Z})$  by

$$J_n = \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix}.$$

- iv) In this paper, all non-archimedean local fields will be understood to be of characteristic zero. If  $F$  is such a field, let  $\mathfrak{o}$  be its ring of integers and  $\mathfrak{p}$  be the maximal ideal of  $\mathfrak{o}$ . Let  $\varpi$  be a generator of  $\mathfrak{p}$ , and let  $q$  be the cardinality of the residue class field  $\mathfrak{o}/\mathfrak{p}$ .
- v) Let  $F$  be as above. If  $L$  is a quadratic field extension of  $F$ , or  $L = F \oplus F$ , let  $(\frac{L}{\mathfrak{p}})$  be the Legendre symbol. By definition,  $(\frac{L}{\mathfrak{p}}) = -1$  if  $L/F$  is an unramified field extension (the *inert case*),  $(\frac{L}{\mathfrak{p}}) = 0$  if  $L/F$  is a ramified field extension (the *ramified case*), and  $(\frac{L}{\mathfrak{p}}) = 1$  if  $L = F \oplus F$  (the *split case*). In the field case, let  $\bar{x}$  denote the Galois conjugate of  $x \in L$ . In the split case, let  $(\bar{x}, y) = (y, x)$ . In all cases, the norm is defined by  $N(x) = x\bar{x}$ . If  $L$  is a field, then let  $\mathfrak{o}_L$  be its ring of integers. If  $L = F \oplus F$ , then let  $\mathfrak{o}_L = \mathfrak{o} \oplus \mathfrak{o}$ . Let  $\varpi_L$  be a generator of  $\mathfrak{p}_L$  if  $L$  is a field, and set  $\varpi_L = (\varpi, 1)$  if  $L$  is not a field. We fix the following ideal in  $\mathfrak{o}_L$ ,

$$\mathfrak{P} := \mathfrak{p}\mathfrak{o}_L = \begin{cases} \mathfrak{p}_L & \text{if } (\frac{L}{\mathfrak{p}}) = -1, \\ \mathfrak{p}_L^2 & \text{if } (\frac{L}{\mathfrak{p}}) = 0, \\ \mathfrak{p} \oplus \mathfrak{p} & \text{if } (\frac{L}{\mathfrak{p}}) = 1. \end{cases} \quad (2)$$

Here,  $\mathfrak{p}_L$  is the maximal ideal of  $\mathfrak{o}_L$  when  $L$  is a field extension. Note that  $\mathfrak{P}$  is prime only if  $(\frac{L}{\mathfrak{p}}) = -1$ . We have  $\mathfrak{P}^n \cap \mathfrak{o} = \mathfrak{p}^n$  for all  $n \geq 0$ .

- vi) We fix additive characters once and for all, as follows. If  $F$  is a non-archimedean local field,  $\psi$  is required to have conductor  $\mathfrak{o}$ . If  $F = \mathbb{R}$ , then  $\psi(x) = e^{-2\pi ix}$ . For any  $a \in F$ , let  $\psi^a(x) = \psi(ax)$ .

### The quadratic extension

Let  $F$  be a non-archimedean local field of characteristic zero, or  $F = \mathbb{R}$ . The unitary groups we shall be working with are defined with respect to a quadratic extension  $L/F$ . We shall now explain the conventions for this quadratic extension. We fix three elements  $\mathbf{a}, \mathbf{b}, \mathbf{c} \in F$  such that  $\mathbf{d} := \mathbf{b}^2 - 4\mathbf{a}\mathbf{c} \neq 0$ . Then let

$$L = \begin{cases} F(\sqrt{\mathbf{d}}) & \text{if } \mathbf{d} \notin F^{\times 2}, \\ F \oplus F & \text{if } \mathbf{d} \in F^{\times 2}. \end{cases} \quad (3)$$

We shall make the following **assumptions**.

- If  $F$  is non-archimedean, assume that  $\mathbf{a}, \mathbf{b} \in \mathfrak{o}$  and  $\mathbf{c} \in \mathfrak{o}^\times$ . Assume moreover that if  $\mathbf{d} \notin F^{\times 2}$ , then  $\mathbf{d}$  is the generator of the discriminant of  $L/F$ , and if  $\mathbf{d} \in F^{\times 2}$ , then  $\mathbf{d} \in \mathfrak{o}^\times$ .
- If  $F = \mathbb{R}$ , assume that  $S = \begin{bmatrix} \mathbf{a} & \mathbf{b}/2 \\ \mathbf{b}/2 & \mathbf{c} \end{bmatrix} \in \text{Mat}_{2,2}(\mathbb{R})$  is a positive definite matrix. Equivalently,  $\mathbf{c} > 0$  and  $\mathbf{d} < 0$ .

Hence, if  $F = \mathbb{R}$ , we always assume that  $L = \mathbb{C}$ . In all cases let

$$\alpha = \begin{cases} \frac{\mathbf{b} + \sqrt{\mathbf{d}}}{2\mathbf{c}} & \text{if } L \text{ is a field,} \\ \left( \frac{\mathbf{b} + \sqrt{\mathbf{d}}}{2\mathbf{c}}, \frac{\mathbf{b} - \sqrt{\mathbf{d}}}{2\mathbf{c}} \right) & \text{if } L = F \oplus F. \end{cases} \quad (4)$$

An important role will be played by the matrix

$$\eta = \begin{bmatrix} 1 & 0 \\ \alpha & 1 \\ & 1 & -\bar{\alpha} \\ & 0 & 1 \end{bmatrix}. \quad (5)$$

We further define

$$\eta_0 = \begin{cases} \eta & \text{if } F \text{ is } p\text{-adic,} \\ \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \\ & 1 & i \\ & i & 1 \end{bmatrix} & \text{if } F = \mathbb{R}. \end{cases} \quad (6)$$

### Algebraic groups

For simplicity we will make all definitions over the local field  $F$ , but it is clear how to define the corresponding global objects.

i) Let  $H = \mathrm{GSp}_4$  and  $G_j = \mathrm{GU}(j, j; L)$  be the algebraic  $F$ -groups whose  $F$ -points are given by

$$H(F) = \{g \in \mathrm{GL}_4(F) \mid {}^t g J_2 g = \mu_2(g) J_2, \mu_2(g) \in F^\times\}, \quad (7)$$

$$G_j(F) = \{g \in \mathrm{GL}_{2j}(L) \mid {}^t \bar{g} J_j g = \mu_j(g) J_j, \mu_j(g) \in F^\times\}. \quad (8)$$

ii) We define, for  $\zeta \in L^\times$  and  $\begin{bmatrix} a & b \\ c & d \end{bmatrix} \in G_1(F)$ ,

$$m_1(\zeta) = \begin{bmatrix} \zeta & & & \\ & 1 & & \\ & & \bar{\zeta}^{-1} & \\ & & & 1 \end{bmatrix}, \quad m_2\left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right) = \begin{bmatrix} 1 & & & b \\ & a & & \\ & & \bar{a}d - b\bar{c} & \\ & c & & d \end{bmatrix}. \quad (9)$$

iii) Let  $P$  be the standard maximal parabolic subgroup of  $G_2(F)$  with a non-abelian unipotent radical. Let  $P = MN$  be the Levi decomposition of  $P$ . We have  $M = M^{(1)}M^{(2)}$ , where

$$M^{(1)}(F) = \{m_1(\zeta) \mid \zeta \in L^\times\}, \quad (10)$$

$$M^{(2)}(F) = \{m_2(g) \mid g \in G_1(F)\}, \quad (11)$$

$$N(F) = \left\{ \begin{bmatrix} 1 & z & & \\ & 1 & & \\ & & 1 & \\ & & & -\bar{z} & 1 \end{bmatrix} \begin{bmatrix} 1 & x & y \\ & 1 & \bar{y} \\ & & 1 \end{bmatrix} \mid x \in F, y, z \in L \right\}. \quad (12)$$

The modular factor of the parabolic  $P$  is given by

$$\delta_P(m_1(\zeta)m_2(g)) = |N(\zeta)\mu_1^{-1}(g)|^3, \quad (13)$$

where  $|\cdot|$  is the normalized absolute value on  $F$ .

iv) Let  $P_{12}$  be the maximal parabolic subgroup of  $G_3$ , defined by

$$P_{12} = G_3 \cap \begin{bmatrix} * & * & * & * & * & * \\ * & * & * & * & * & * \\ * & * & * & * & * & * \\ & & & * & * & * \\ & & & * & * & * \\ & & & * & * & * \end{bmatrix}. \quad (14)$$

Let  $P_{12} = M_{12}N_{12}$  be the Levi decomposition, with

$$M_{12}(F) := \left\{ m(A, v) = \begin{bmatrix} A & 0 \\ 0 & v^t \bar{A}^{-1} \end{bmatrix} \mid A \in \mathrm{GL}_3(L), v \in F^\times \right\},$$

$$N_{12}(F) := \left\{ \begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix} \mid b \in \mathrm{Mat}_{3,3}(L), {}^t \bar{b} = b \right\}.$$

The modular function of  $P_{12}$  is given by

$$\delta_{12}\left(\begin{bmatrix} A & \\ & v^t \bar{A}^{-1} \end{bmatrix}\right) = |v|^{-3} N(\det(A))^3, \quad v \in F^\times, A \in \mathrm{GL}_3(L). \quad (15)$$

v) Let  $\iota$  be the embedding of  $\{(g_1, g_2) \in G_1(F) \times G_2(F) : \mu_1(g_1) = \mu_2(g_2)\}$  into  $G_3(F)$  defined by

$$\iota\left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}, \begin{bmatrix} A & B \\ C & D \end{bmatrix}\right) = \begin{bmatrix} A & B & \\ & a & -b \\ C & D & \\ & -c & d \end{bmatrix}. \quad (16)$$

### Congruence subgroups

Assuming that  $F$  is  $p$ -adic, we will use the following notation for congruence subgroups,

$$K^{(0)}(\mathfrak{P}^n) = G_1(\mathfrak{o}) \cap \begin{bmatrix} \mathfrak{o}_L & \mathfrak{o}_L \\ \mathfrak{P}^n & \mathfrak{o}_L \end{bmatrix}, \quad (17)$$

$$K^{(1)}(\mathfrak{P}^n) = G_1(\mathfrak{o}) \cap \begin{bmatrix} 1 + \mathfrak{P}^n & \mathfrak{o}_L \\ \mathfrak{P}^n & \mathfrak{o}_L \end{bmatrix}, \quad (18)$$

$$\begin{aligned} K_1^{(1)}(\mathfrak{P}^n) &= U(1, 1; L)(\mathfrak{o}) \cap K^{(1)}(\mathfrak{P}^n) \\ &= U(1, 1; L)(\mathfrak{o}) \cap \begin{bmatrix} 1 + \mathfrak{P}^n & \mathfrak{o}_L \\ \mathfrak{P}^n & \mathfrak{o}_L \end{bmatrix} = U(1, 1; L)(\mathfrak{o}) \cap \begin{bmatrix} 1 + \mathfrak{P}^n & \mathfrak{o}_L \\ \mathfrak{P}^n & 1 + \mathfrak{P}^n \end{bmatrix}, \end{aligned} \quad (19)$$

$$K^{(1)}(\mathfrak{p}^n) = \mathrm{GL}_2(\mathfrak{o}) \cap \begin{bmatrix} 1 + \mathfrak{p}^n & \mathfrak{o} \\ \mathfrak{p}^n & \mathfrak{o} \end{bmatrix}. \quad (20)$$

If  $\tau$  is an irreducible, admissible representation of  $\mathrm{GL}_n(F)$ , we let  $a(\tau)$  be the non-negative integer such that  $\mathfrak{p}^{a(\tau)}$  is the conductor of  $\tau$ ; see Theorem 1.2.2 for a characterization in the  $\mathrm{GL}_2$  case. If  $\chi$  is a character of  $F^\times$ , then  $a(\chi)$  is the smallest non-negative integer such that  $\chi$  is trivial on  $\mathfrak{o}^\times \cap (1 + \mathfrak{p}^{a(\chi)})$ .

## Representations of $\mathrm{GL}_2(\mathbb{R})$

If  $p$  is a positive integer and  $\mu \in \mathbb{C}$ , we let  $\mathcal{D}_{p,\mu}$  be the irreducible representation of  $\mathrm{GL}_2(\mathbb{R})$  with minimal weight  $p+1$  and central character satisfying  $a \mapsto a^{2\mu}$  for  $a > 0$ . Every other irreducible, admissible representation of  $\mathrm{GL}_2(\mathbb{R})$  is of the form  $\beta_1 \times \beta_2$  with characters  $\beta_1, \beta_2$  of  $\mathbb{R}^\times$ ; see (26). Note that, if  $\mu \in i\mathbb{R}$ , then  $\mathcal{D}_{p,\mu}$  is a discrete series representation.

# 1 Distinguished vectors in local representations

In this section we will develop some local theory, both archimedean and non-archimedean, which will be utilized in subsequent sections on global integral representations. Recall the definitions of the groups  $G_j = \mathrm{GU}(j, j; L)$  from (8). The local theory will exhibit distinguished vectors in certain parabolically induced representations of  $G_2(F)$ , where  $F = \mathbb{R}$  or  $F$  is  $p$ -adic. We will also study the behavior of these vectors under local intertwining operators. Since the distinguished vectors are characterized by right transformation properties, the intertwining operators map distinguished vectors to distinguished vectors. This fact will later be applied to obtain the functional equation of global  $L$ -functions.

Unless otherwise noted,  $F$  is a non-archimedean local field of characteristic zero, or  $F = \mathbb{R}$ . We let  $L, \alpha, \eta$  be as in (3), (4), (5), respectively.

### 1.1 Parabolic induction to $\mathrm{GU}(2, 2)$

Let  $(\tau, V_\tau)$  be an irreducible, admissible, infinite-dimensional representation of  $\mathrm{GL}_2(F)$ , and let  $\chi_0$  be a character of  $L^\times$  such that  $\chi_0|_{F^\times}$  coincides with  $\omega_\tau$ , the central character of  $\tau$ . Then the pair  $(\chi_0, \tau)$  defines a representation of  $G_1(F) \cong M^{(2)}(F)$  on the same space  $V_\tau$  via

$$\tau(\lambda g) = \chi_0(\lambda)\tau(g), \quad \lambda \in L^\times, g \in \mathrm{GL}_2(F). \quad (21)$$

We denote this representation by  $\chi_0 \times \tau$ . Every irreducible, admissible representation of  $G_1(F)$  is of the form (21). If  $V_\tau$  is a space of functions on  $\mathrm{GL}_2(F)$  on which  $\mathrm{GL}_2(F)$  acts by right translation, then  $\chi_0 \times \tau$  can be realized as a space of functions on  $M^{(2)}(F)$  on which  $M^{(2)}(F)$  acts by right translation. This is accomplished by extending every  $W \in V_\tau$  to a function on  $M^{(2)}(F)$  via

$$W(\lambda g) = \chi_0(\lambda)W(g), \quad \lambda \in L^\times, g \in \mathrm{GL}_2(F). \quad (22)$$

If  $s$  is a complex parameter,  $\chi$  is any character of  $L^\times$  and  $\chi_0 \times \tau$  is a representation of  $M^{(2)}(F)$  as above, we denote by  $I(s, \chi, \chi_0, \tau)$  the induced representation of  $G_2(F)$  consisting of functions  $f : G_2(F) \rightarrow V_\tau$  with the transformation property

$$f(m_1(\zeta)m_2(b)ng) = |N(\zeta)\mu_1^{-1}(b)|^{3(s+\frac{1}{2})}\chi(\zeta)(\chi_0 \times \tau)(b)f(g) \quad (23)$$

for  $\zeta \in L^\times$  and  $b \in G_1(F)$ .

Now taking  $V_\tau$  to be the Whittaker model of  $\tau$  with respect to the character  $\psi$ , if we associate to each  $f$  as above the function on  $G_2(F)$  given by  $W_f(g) = f(g)(1)$ , then we obtain another model  $I_W(s, \chi, \chi_0, \tau)$  of  $I(s, \chi, \chi_0, \tau)$  consisting of functions  $W : G_2(F) \rightarrow \mathbb{C}$ . These functions satisfy

$$W(m_1(\zeta)m_2(\begin{bmatrix} \lambda & \\ & \lambda \end{bmatrix})g) = |N(\zeta\lambda^{-1})|^{3(s+\frac{1}{2})}\chi(\zeta)\chi_0(\lambda)W(g), \quad \zeta, \lambda \in L^\times, \quad (24)$$

and

$$W\left(\begin{bmatrix} 1 & z \\ & 1 \\ & & 1 \\ & -\bar{z} & 1 \end{bmatrix}\begin{bmatrix} 1 & x & y \\ & 1 & \bar{y} \\ & & 1 \end{bmatrix}g\right) = \psi(w)W(g), \quad w, x, y, z \in F, \quad y, z \in L. \quad (25)$$

Assume on the other hand that  $\tau$  is a parabolically induced representation  $\beta_1 \times \beta_2$ , not necessarily irreducible, with characters  $\beta_1, \beta_2 : F^\times \rightarrow \mathbb{C}^\times$ . The standard model of  $\beta_1 \times \beta_2$  consists of functions  $\varphi : \mathrm{GL}_2(F) \rightarrow \mathbb{C}$  with the transformation property

$$\varphi\left(\begin{bmatrix} a & b \\ d & \end{bmatrix}g\right) = |ad^{-1}|^{1/2} \beta_1(a)\beta_2(d)\varphi(g) \quad \text{for all } a, d \in F^\times, b \in F, g \in \mathrm{GL}_2(F). \quad (26)$$

If we associate to  $f$  as in (23), now taking values in the standard model of  $\beta_1 \times \beta_2$ , the function  $\Phi_f$  on  $G_2(F)$  given by  $\Phi_f(g) = f(g)(1)$ , then we obtain another model of  $I(s, \chi, \chi_0, \tau)$ , which we denote by  $I_\Phi(s, \chi, \chi_0, \tau)$ . It consists of functions  $\Phi : G_2(F) \rightarrow \mathbb{C}$  with the transformation property

$$\begin{aligned} \Phi\left(\begin{bmatrix} \zeta & * & * & * \\ & \lambda & * & * \\ & & \bar{\zeta}^{-1}N(\lambda) & * \\ & & & * \end{bmatrix}\begin{bmatrix} 1 & & & \\ & a & & \\ & & ad & \\ & & & d \end{bmatrix}g\right) \\ = |N(\zeta\lambda^{-1})|^{3(s+\frac{1}{2})} |a|^{-3s-1} |d|^{-3s-2} \chi(\zeta)\chi_0(\lambda)\beta_1(a)\beta_2(d)\Phi(g) \end{aligned} \quad (27)$$

for all  $\zeta, \lambda \in L^\times, a, d \in F^\times$ .

### Intertwining operators

Assume that  $\tau$  is generic, and let  $\chi, \chi_0$  be as above. For  $f \in I(s, \chi, \chi_0, \tau)$  with  $\mathrm{Re}(s)$  large enough, the local intertwining operator is defined by

$$(M(s)f)(g) = \int_{N(F)} f(w_1 ng) dn, \quad w_1 = \begin{bmatrix} & & 1 & \\ & & 1 & \\ -1 & & & \\ & & & 1 \end{bmatrix}. \quad (28)$$

Calculations show that  $M(s)$  defines an intertwining map

$$M(s) : I(s, \chi, \chi_0, \tau) \longrightarrow I(-s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau), \quad (29)$$

where by  $\chi\tau$  we mean the twist  $(\chi|_{F^\times}) \otimes \tau$ . It is easily checked that the above formula (28) also defines intertwining operators  $M(s)$  from  $I_\Phi(s, \chi, \chi_0, \tau)$  to  $I_\Phi(-s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau)$  and from  $I_W(s, \chi, \chi_0, \tau)$  to  $I_W(-s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau)$ . In Corollary 1.2.4 (non-archimedean case) and Corollary 1.3.7 (archimedean case) we will identify a distinguished element

$$W^\# = W^\#(\cdot, s, \chi, \chi_0, \tau)$$

in  $I_W(s, \chi, \chi_0, \tau)$ . This distinguished function will have the property

$$M(s)W^\#(\cdot, s, \chi, \chi_0, \tau) = K(s)W^\#(\cdot, -s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau). \quad (30)$$

with a “constant”  $K(s)$  (independent of  $g \in G_2(F)$ , but dependent on  $s$ , as well as  $\chi, \chi_0$  and  $\tau$ ). In most cases  $K(s)$  exists because  $W^\#$  is characterized, up to scalars, by *right* transformation

properties. An exception is the archimedean “different parity” Case C, defined in Sect. 1.3, in which case said right transformation properties characterize a *two*-dimensional space. In this case the existence of the function  $K(s)$  such that (30) holds will follow from explicit calculations. Note that if  $\eta_0 \in G_2(F)$  is such that  $W^\#(\eta_0) = 1$ , then we obtain the formula

$$K(s) = \int_{N(F)} W^\#(w_1 n \eta_0, s, \chi, \chi_0, \tau) dn \quad (31)$$

by evaluating at  $\eta_0$ . Explicitly,

$$K(s) = \int_L \int_{L/F} \int_{F} W^\#(w_1 \begin{bmatrix} 1 & z & & \\ & 1 & & \\ & & 1 & \\ & -\bar{z} & 1 \end{bmatrix} \begin{bmatrix} 1 & x & y \\ & 1 & \bar{y} \\ & & 1 \end{bmatrix} \eta_0) dx dy dz. \quad (32)$$

Our goal in Sects. 1.4 and 1.5 will be to calculate the function  $K(s)$ . We will then also be more precise about the measures on  $F$  and  $L$  used in (32).

## 1.2 Distinguished vectors: non-archimedean case

In this section let  $F$  be a non-archimedean local field of characteristic zero. Let  $\tau$  be any irreducible, admissible representation of  $\mathrm{GL}_2(F)$ , and let  $\chi_0$  be a character of  $L^\times$  such that  $\chi_0|_{F^\times} = \omega_\tau$ , the central character of  $\tau$ . Let  $\Lambda$  be an unramified character of  $L^\times$ , and let  $\chi$  be the character of  $L^\times$  defined by

$$\chi(\zeta) = \Lambda(\bar{\zeta})^{-1} \chi_0(\bar{\zeta})^{-1}. \quad (33)$$

For a complex parameter  $s$ , let  $I(s, \chi, \chi_0, \tau)$  be as in Sect. 1.1. Let  $K^{G_2} = G_2(F) \cap \mathrm{GL}_4(\mathfrak{o}_L)$ , a maximal compact subgroup. We define the principal congruence subgroups  $\Gamma(\mathfrak{P}^r) := \{g \in G_2(F) \mid g \equiv 1 \pmod{\mathfrak{P}^r}\}$  with  $\mathfrak{P}$  as in (2). For  $r = 0$  we understand that  $\Gamma(\mathfrak{P}^r) = K^{G_2}$ . For any  $m \geq 0$ , we let

$$\eta_m = \begin{bmatrix} 1 & 0 \\ \alpha \varpi^m & 1 \\ & 1 & -\bar{\alpha} \varpi^m \\ 0 & 1 \end{bmatrix}. \quad (34)$$

For systematic reasons, we let  $\eta_\infty$  be the identity matrix. Note that  $\eta_0 = \eta$ ; see (5).

**1.2.1 Proposition.** *For any  $r \geq 0$  the following disjoint double coset decompositions hold,*

$$G_2(F) = \bigsqcup_{0 \leq m \leq \infty} P(F) \eta_m K^H = \bigsqcup_{0 \leq m \leq r} P(F) \eta_m K^H \Gamma(\mathfrak{P}^r). \quad (35)$$

Moreover, for any  $0 \leq m < r$ , we have

$$P(F) \eta_m K^H \Gamma(\mathfrak{P}^r) = P(F) \eta_m K^H. \quad (36)$$

**Proof.** Using the Iwasawa decomposition, (35) follows from

$$K^{G_2} = \bigsqcup_{0 \leq m \leq \infty} P(\mathfrak{o}) \eta_m K^H = \bigsqcup_{0 \leq m \leq r} P(\mathfrak{o}) \eta_m K^H \Gamma(\mathfrak{P}^r). \quad (37)$$

One can show that the double cosets on the right hand side of (37) are disjoint by observing that the function

$$K^{G_2} \ni g \mapsto \min(v((gJ^t g)_{3,2}), v((gJ^t g)_{3,4}))$$

takes different values on the double cosets. We take the above function modulo  $\mathfrak{P}^r$  for the disjointness of the double cosets involving  $\Gamma(\mathfrak{P}^r)$ . Knowing disjointness, one obtains the second equality in (37) by multiplying the double cosets by  $\Gamma(\mathfrak{P}^r)$  on the right. We only sketch a proof of the first equality in (37). The first step consists in showing that  $K^{G_2} = P(\mathfrak{o})K^H\Gamma(\mathfrak{P}) \sqcup P(\mathfrak{o})\eta K^H\Gamma(\mathfrak{P})$ , which can be done explicitly by considering the three cases – inert, ramified and split – separately. Then, for  $g \in P(\mathfrak{o})\gamma_0 K^H$  with  $\gamma_0 \in \Gamma(\mathfrak{P})$  or  $\gamma_0 \in \eta\Gamma(\mathfrak{P})$ , observe that

$$\gamma_0 \in G_2(F) \cap \begin{bmatrix} \mathfrak{o}_L^\times & \mathfrak{P} & \mathfrak{o}_L & \mathfrak{o}_L \\ \mathfrak{o}_L & \mathfrak{o}_L^\times & \mathfrak{o}_L & \mathfrak{o}_L \\ \mathfrak{P} & \mathfrak{P} & \mathfrak{o}_L^\times & \mathfrak{o}_L \\ \mathfrak{P} & \mathfrak{P} & \mathfrak{P} & \mathfrak{o}_L^\times \end{bmatrix}.$$

Using appropriate matrix identities one can show, for any  $\gamma_0$  in this set, that there exist  $p \in P(\mathfrak{o})$ ,  $h \in K^H$  and a unique  $m \in \{0, 1, 2, \dots, \infty\}$  such that  $\gamma_0 = p\eta_m h$ ; this completes the proof of (35).

To prove (36), we rewrite (35) as

$$G_2(F) = \bigsqcup_{0 \leq m < r} P(F)\eta_m K^H \sqcup X, \quad X = \bigsqcup_{r \leq m \leq \infty} P(F)\eta_m K^H,$$

and also

$$G_2(F) = \bigsqcup_{0 \leq m < r} P(F)\eta_m K^H \Gamma(\mathfrak{P}^r) \sqcup Y, \quad Y = P(F)\eta_r K^H \Gamma(\mathfrak{P}^r).$$

For  $m \geq r$ , we have  $\eta_m \in P(F)K^H\Gamma(\mathfrak{P}^r) = P(F)\eta_r K^H\Gamma(\mathfrak{P}^r)$ . Hence  $X \subset Y$ . Evidently, for  $m < r$ , we have  $P(F)\eta_m K^H \subset P(F)\eta_r K^H\Gamma(\mathfrak{P}^r)$ . It follows that  $P(F)\eta_m K^H = P(F)\eta_r K^H\Gamma(\mathfrak{P}^r)$ . ■

We recall the standard newform theory for  $\mathrm{GL}_2$ . Let the congruence subgroup  $K^{(1)}(\mathfrak{p}^n)$  be as in (20). The following result is well known (see [8], [12]).

**1.2.2 Theorem.** *Let  $(\tau, V_\tau)$  be a generic, irreducible, admissible representation of  $\mathrm{GL}_2(F)$ . Then the spaces*

$$V_\tau(n) = \{v \in V_\tau \mid \tau(g)v = v \text{ for all } g \in K^{(1)}(\mathfrak{p}^n)\}$$

*are non-zero for  $n$  large enough. If  $n$  is minimal with  $V_\tau(n) \neq 0$ , then  $\dim(V_\tau(n)) = 1$ . For  $r \geq n$ , we have  $\dim(V_\tau(r)) = r - n + 1$ .*

If  $n$  is minimal such that  $V_\tau(n) \neq 0$ , then  $\mathfrak{p}^n$  is called the *conductor* of  $\tau$ , and we write  $n = a(\tau)$ . Any non-zero vector in  $V_\tau(a(\tau))$  is called a *local newform*. The following theorem is a local newforms result for the induced representations  $I(s, \chi, \chi_0, \tau)$  with respect to the congruence subgroups  $K^H\Gamma(\mathfrak{P}^r)$ .

**1.2.3 Theorem.** *Let  $(\tau, V_\tau)$  be a generic, irreducible, admissible representation of  $\mathrm{GL}_2(F)$  with central character  $\omega_\tau$  and conductor  $\mathfrak{p}^n$ . Let  $\chi_0$  be a character of  $L^\times$  such that  $\chi_0|_{F^\times} = \omega_\tau$  and  $\chi_0((1 + \mathfrak{P}^n) \cap \mathfrak{o}_L^\times) = 1$ , and let  $\chi$  be the character of  $L^\times$  defined by (33), where  $\Lambda$  is unramified. Let*

$$V(r) := \{\phi \in I(s, \chi, \chi_0, \tau) \mid \phi(g\gamma, s) = \phi(g, s) \text{ for all } g \in G(F), \gamma \in K^H\Gamma(\mathfrak{P}^r)\}$$

for a non-negative integer  $r$ . Then

$$\dim(V(r)) = \begin{cases} \frac{(r-n+1)(r-n+2)}{2} & \text{if } r \geq n, \\ 0 & \text{if } r < n. \end{cases}$$

**Proof.** Let  $\phi \in V(r)$ . By Proposition 1.2.1,  $\phi$  is completely determined by its values on  $\eta_m$ ,  $0 \leq m \leq r$ . For such  $m$ , and any  $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in K^{(1)}(\mathfrak{p}^{r-m})$ , we have  $A := m_2(g) \in M(F)N(F) \cap \eta_m K^H \Gamma(\mathfrak{P}^r) \eta_m^{-1}$ . It follows that  $\phi(\eta_m) = \phi(A\eta_m) = \tau(g)\phi(\eta_m)$ . Hence, for  $0 \leq m \leq r$ , the vector  $v_m := \phi(\eta_m)$  lies in  $V_\tau(r-m)$ . Since the conductor of  $\tau$  is  $\mathfrak{p}^n$ , we conclude that  $v_m = 0$  if  $r-m < n$ . Therefore  $\dim(V(r)) = 0$  for all  $r < n$ .

Now suppose that  $r \geq n$ . We will show that, for any  $m$  such that  $r-m \geq n$ , if  $v_m$  is chosen to be any vector in  $V_\tau(r-m)$ , then we obtain a well-defined function  $\phi$  in  $V(r)$ . For  $m=r$  this is easy to check, since in this case  $n=0$  and all the data is unramified. Assume therefore that  $r > m$ . We have to show that for  $m_1 n_1 \eta_m k_1 \gamma_1 = m_2 n_2 \eta_m k_2 \gamma_2$ , with  $m_i \in M(F)$ ,  $n_i \in N(F)$ ,  $k_i \in K^H$  and  $\gamma_i \in \Gamma(\mathfrak{P}^r)$ ,

$$|N(\zeta_1) \cdot \mu_1^{-1}|^{3(s+1/2)} \chi(\zeta_1) (\chi_0 \times \tau) \left( \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix} \right) v_m = |N(\zeta_2) \cdot \mu_2^{-1}|^{3(s+1/2)} \chi(\zeta_2) (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \right) v_m. \quad (38)$$

We have  $\eta_m^{-1} m_2^{-1} m_1 n^* \eta_m \in K^H \Gamma(\mathfrak{P}^r)$ , where  $n^* \in N(F)$  depends on  $m_1, m_2, n_1, n_2$ . Write

$$m_2^{-1} m_1 = \begin{bmatrix} \zeta & & & \\ & \tilde{a} & & \tilde{b} \\ & & \mu \bar{\zeta}^{-1} & \\ \tilde{c} & & & \tilde{d} \end{bmatrix}.$$

By definition,  $\zeta_1 = \zeta_2 \zeta$  and  $\mu_1 = \mu_2 \mu$ . We have  $\zeta \in \mathfrak{o}_L^\times$  and  $\mu \in \mathfrak{o}^\times$ . Hence (38) is equivalent to

$$\chi(\zeta) (\chi_0 \times \tau) \left( \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix} \right) v_m = (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \right) v_m. \quad (39)$$

One can check that  $\tilde{a} \bar{\zeta}^{-1} \in 1 + \mathfrak{P}^{r-m}$  and  $\tilde{c} \in \mathfrak{P}^{r-m}$ . Hence, using the definition of  $\chi, \chi_0$  (with unramified  $\Lambda$ ) and the fact that  $v_m \in V_\tau(r-m)$ ,

$$\begin{aligned} \chi(\zeta) (\chi_0 \times \tau) \left( \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix} \right) v_m &= \chi(\zeta) (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \begin{bmatrix} \tilde{a} & \tilde{b} \\ \tilde{c} & \tilde{d} \end{bmatrix} \right) v_m \\ &= \chi(\zeta) \chi_0(\tilde{a}) (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \begin{bmatrix} 1 & \tilde{b}/\tilde{a} \\ \tilde{c}/\tilde{a} & \tilde{d}/\tilde{a} \end{bmatrix} \right) v_m \\ &= \chi_0(\bar{\zeta}^{-1}) \chi_0(\tilde{a}) (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \right) v_m \\ &= (\chi_0 \times \tau) \left( \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \right) v_m, \end{aligned}$$

as claimed. Now, using the formula for  $\dim(V_\tau(r-m))$  from Theorem 1.2.2 completes the proof of the theorem. ■

Assume that  $W^{(0)}$  is the newform in the Whittaker model of  $\tau$  with respect to an additive character of conductor  $\mathfrak{o}$ . Then it is known that  $W^{(0)}(1) \neq 0$ , so that this function can be normalized by  $W^{(0)}(1) = 1$ . The following is an immediate consequence of the above theorem (and its proof).

**1.2.4 Corollary.** *There exists a unique element  $W^\#(\cdot, s)$  in  $Iw(s, \chi, \chi_0, \tau)$  with the properties*

$$W^\#(gk, s) = W^\#(g, s) \quad \text{for } g \in G_2(F), k \in K^H \Gamma(\mathfrak{P}^n), \quad (40)$$

and

$$W^\#(\eta_0, s) = 1, \quad (41)$$

where  $\eta_0 = \eta$  as in (6). The function  $W^\#(\cdot, s)$  is supported on  $P(F)\eta_0 K^H \Gamma(\mathfrak{P}^n)$ . On this double coset,

$$W^\#(m_1(\zeta)m_2(g)\eta_0, s) = |N(\zeta) \cdot \mu_1^{-1}(g)|^{3(s+1/2)} \chi(\zeta) W^{(0)}(g), \quad (42)$$

where  $\zeta \in L^\times$ ,  $g \in G_1(F)$ , and  $W^{(0)}$  is the newform in  $V_\tau$ , normalized by  $W^{(0)}(1) = 1$ , and extended to a function on  $G_1(F)$  via the character  $\chi_0$  (see (22)).

### 1.3 Distinguished vectors: archimedean case

Let  $F = \mathbb{R}$  and  $L = \mathbb{C}$ , and  $G_2 = \mathrm{GU}(2, 2; \mathbb{C})$  as in the notations. Consider the symmetric domains  $\mathbb{H}_2 := \{Z \in \mathrm{Mat}_{2,2}(\mathbb{C}) \mid i(^t\bar{Z} - Z) \text{ is positive definite}\}$  and  $\mathfrak{h}_2 := \{Z \in \mathbb{H}_2 \mid {}^t Z = Z\}$ . The group  $G_2^+(\mathbb{R}) := \{g \in G_2(\mathbb{R}) \mid \mu_2(g) > 0\}$  acts on  $\mathbb{H}_2$  via  $(g, Z) \mapsto g\langle Z \rangle$ , where

$$g\langle Z \rangle = (AZ + B)(CZ + D)^{-1}, \text{ for } g = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \in G_2^+(\mathbb{R}), Z \in \mathbb{H}_2.$$

Under this action,  $\mathfrak{h}_2$  is stable by  $H^+(\mathbb{R}) = \mathrm{GSp}_4^+(\mathbb{R})$ . The group  $K_\infty^{G_2} = \{g \in G_2^+(\mathbb{R}) : \mu_2(g) = 1, g\langle i_2 \rangle = i_2\}$  is a maximal compact subgroup of  $G_2^+(\mathbb{R})$ . Here,  $i_2 = \begin{bmatrix} i & \\ & i \end{bmatrix} \in \mathbb{H}_2$ . By the Iwasawa decomposition

$$G_2(\mathbb{R}) = M^{(1)}(\mathbb{R})M^{(2)}(\mathbb{R})N(\mathbb{R})K_\infty^{G_2}, \quad (43)$$

where  $M^{(1)}(\mathbb{R})$ ,  $M^{(2)}(\mathbb{R})$  and  $N(\mathbb{R})$  are as defined in (10), (11) and (12). For  $g \in G_2^+(\mathbb{R})$  and  $Z \in \mathbb{H}_2$ , let  $J(g, Z) = CZ + D$  be the automorphy factor. Then, for any integer  $l$ , the map

$$k \longmapsto \det(J(k, i_2))^l \quad (44)$$

defines a character  $K_\infty^{G_2} \rightarrow \mathbb{C}^\times$ . Let  $K_\infty^H = K_\infty \cap H^+(\mathbb{R})$ . Then  $K_\infty^H$  is a maximal compact subgroup of  $H^+(\mathbb{R})$ .

Let  $(\tau, V_\tau)$  be a generic, irreducible, admissible representation of  $\mathrm{GL}_2(\mathbb{R})$  with central character  $\omega_\tau$ . Let  $l_2$  be an integer of the same parity as the weights of  $\tau$  (the precise value of  $l_2$  is largely irrelevant, and we will later make a specific choice). Let  $\chi_0$  be the character of  $\mathbb{C}^\times$  such that  $\chi_0|_{\mathbb{R}^\times} = \omega_\tau$  and  $\chi_0(\zeta) = \zeta^{l_2}$  for  $\zeta \in \mathbb{C}^\times$ ,  $|\zeta| = 1$ . Let  $\chi$  be the character of  $\mathbb{C}^\times$  given by

$$\chi(\zeta) = \chi_0(\bar{\zeta})^{-1}. \quad (45)$$

We interpret  $\chi$  as a character of  $M^{(1)}(\mathbb{R}) \cong \mathbb{C}^\times$ . We extend  $\tau$  to a representation of  $G_1(\mathbb{R})$  as in (21). In the archimedean case, we can always realize  $\tau$  as a subrepresentation of a parabolically induced representation  $\beta_1 \times \beta_2$ , with characters  $\beta_1, \beta_2 : \mathbb{R}^\times \rightarrow \mathbb{C}^\times$  (see (26)). We define the complex numbers  $t_1, t_2, p, q$  by

$$\beta_1(a) = a^{t_1}, \quad \beta_2(a) = a^{t_2}, \quad p = t_1 - t_2, \quad q = t_1 + t_2 \quad (46)$$

for  $a > 0$ .

**Remark:** Evidently,  $q$  is related to the central character of  $\tau$  via  $\omega_\tau(a) = a^q$  for  $a > 0$ . The number  $p$  could also be more intrinsically defined via the eigenvalue of the Laplace operator. Note that if  $\tau$  belongs to the principal series and  $\beta_1$  and  $\beta_2$  are interchanged, then  $p$  changes sign; this ambiguity will be irrelevant. We also note that if  $\tau$  is a discrete series representation of lowest weight  $l_1$ , then  $p = l_1 - 1$ .

The induced representation  $I_\Phi(s, \chi, \chi_0, \tau)$  is now a subrepresentation of  $I_\Phi(s, \chi, \chi_0, \beta_1 \times \beta_2)$ . Any  $\Phi \in I_\Phi(s, \chi, \chi_0, \tau)$  satisfies the transformation property (27); in view of the Iwasawa decomposition,  $\Phi$  is determined by its restriction to  $K_\infty^{G_2}$ . Conversely, given a function  $\Phi : K_\infty^{G_2} \rightarrow \mathbb{C}$ , it can be extended to a function on  $G_2(\mathbb{R})$  with the property (27) if and only if

$$\Phi(\hat{\zeta}_1 k) = \zeta^{l_2} \Phi(k), \quad \Phi(\hat{\zeta}_2 k) = \zeta^{l_2} \Phi(k), \quad (47)$$

for all  $\zeta \in S^1$  and  $k \in K_\infty^{G_2}$ . Here, we used the notation

$$\hat{\zeta}_1 = \begin{bmatrix} \zeta & & \\ & 1 & \\ & & \zeta \end{bmatrix}, \quad \hat{\zeta}_2 = \begin{bmatrix} 1 & & \\ & \zeta & \\ & & 1 \end{bmatrix}.$$

We will therefore study certain spaces of functions on  $K_\infty^{G_2}$  with the property (47).

### The spaces $W_{m,l,l_2}^\Delta$

We begin by describing the Lie algebra and the finite-dimensional representations of  $K_\infty^{G_2}$ . Let  $\mathfrak{g}$  be the Lie algebra of  $U(2, 2)$ . Let  $X \mapsto {}^t \bar{X}$  be the Cartan involution on  $\mathfrak{g}$ . Let  $\mathfrak{k}$  be the  $+1$  eigenspace and let  $\mathfrak{p}$  be the  $-1$  eigenspace of the Cartan involution. We denote by  $\mathfrak{k}_\mathbb{C}$  and  $\mathfrak{p}_\mathbb{C}$  the complexifications of  $\mathfrak{k}$  and  $\mathfrak{p}$ , respectively. Then

$$\mathfrak{k}_\mathbb{C} = \left\{ \begin{bmatrix} A & B \\ -B & A \end{bmatrix} \mid A, B \in \text{Mat}_{2,2}(\mathbb{C}) \right\}, \quad \mathfrak{p}_\mathbb{C} = \left\{ \begin{bmatrix} A & B \\ B & -A \end{bmatrix} \mid A, B \in \text{Mat}_{2,2}(\mathbb{C}) \right\}.$$

Hence  $\mathfrak{g}_\mathbb{C} = \mathfrak{k}_\mathbb{C} \oplus \mathfrak{p}_\mathbb{C} = \mathfrak{gl}(4, \mathbb{C})$ . The following eight elements constitute a convenient basis for  $\mathfrak{k}_\mathbb{C}$ .

$$U_1 = \frac{1}{2} \begin{bmatrix} 1 & 0 & -i \\ i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad U_2 = \frac{1}{2} \begin{bmatrix} 0 & 1 & -i \\ i & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad V_1 = \frac{1}{2} \begin{bmatrix} -1 & 0 & -i \\ i & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad V_2 = \frac{1}{2} \begin{bmatrix} 0 & -1 & -i \\ i & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix},$$

$$P_+ = \frac{1}{2} \begin{bmatrix} 0 & 1 & -i \\ 0 & i & 0 \\ i & 0 & 1 \end{bmatrix}, \quad P_- = \frac{1}{2} \begin{bmatrix} 0 & 1 & -i \\ 1 & 0 & 0 \\ i & 1 & 0 \end{bmatrix}, \quad Q_+ = \frac{1}{2} \begin{bmatrix} 0 & 0 & -i \\ -1 & 0 & 0 \\ i & -1 & 0 \end{bmatrix}, \quad Q_- = \frac{1}{2} \begin{bmatrix} 0 & -1 & -i \\ 0 & i & 0 \\ i & 0 & -1 \end{bmatrix}.$$

We have

$$\mathfrak{k}_\mathbb{C} = \langle U_1, U_2, P_+, P_- \rangle \oplus \langle V_1, V_2, Q_+, Q_- \rangle \cong \mathfrak{gl}(2, \mathbb{C}) \oplus \mathfrak{gl}(2, \mathbb{C}). \quad (48)$$

The center of  $\mathfrak{k}$  is 2-dimensional, spanned by

$$i(U_1 + U_2 + V_1 + V_2) = \begin{bmatrix} & 1 & \\ & -1 & \\ & & -1 \end{bmatrix} \quad \text{and} \quad i(U_1 + U_2 - V_1 - V_2) = \begin{bmatrix} i & & \\ & i & \\ & & i \end{bmatrix}. \quad (49)$$

The Casimir operators for the two copies of  $\mathfrak{sl}(2, \mathbb{C})$  are given by

$$\Delta_1 = (U_1 - U_2)^2 + 2(P_+ P_- + P_- P_+), \quad \Delta_2 = (V_1 - V_2)^2 + 2(Q_+ Q_- + Q_- Q_+).$$

The irreducible representations of  $\mathfrak{k}_{\mathbb{C}}$  which lift to representations of  $K_{\infty}^{G_2}$  are parametrized by four integers,

- $m_1$ : highest weight of  $\langle U_1 - U_2, P_+, P_- \rangle$ ,  $n_1$ : eigenvalue of  $U_1 + U_2$ ,
- $m_2$ : highest weight of  $\langle V_1 - V_2, Q_+, Q_- \rangle$ ,  $n_2$ : eigenvalue of  $V_1 + V_2$ ,

subject to the condition that they all have the same parity and that  $m_1, m_2 \geq 0$ . The parity condition is a consequence of overlapping one-parameter subgroups generated by  $U_1 \pm U_2$  and  $V_1 \pm V_2$ . Let  $\rho_{m_1, n_1, m_2, n_2}$  be the irreducible representation of  $K_{\infty}^{G_2}$  corresponding to  $(m_1, n_1, m_2, n_2)$ . Then  $\dim \rho_{m_1, n_1, m_2, n_2} = (m_1 + 1)(m_2 + 1)$ , and the contragredient representation is given by  $\tilde{\rho}_{m_1, n_1, m_2, n_2} = \rho_{m_1, -n_1, m_2, -n_2}$ .

**1.3.1 Lemma.** *Let  $m_1, n_1, m_2, n_2$  be integers of the same parity with  $m_1, m_2 \geq 0$ .*

- i) Any vector  $v$  in  $\rho_{m_1, n_1, m_2, n_2}$  satisfies

$$\Delta_1 v = m_1(m_1 + 2)v, \quad \Delta_2 v = m_2(m_2 + 2)v, \quad (U_1 + U_2)v = n_1 v, \quad (V_1 + V_2)v = n_2 v. \quad (50)$$

- ii) The representation  $\rho_{m_1, n_1, m_2, n_2}$  of  $K_{\infty}^{G_2}$  contains the trivial representation of  $K_{\infty}^H$  if and only if  $m_1 = m_2$  and  $n_1 = -n_2$ . If these conditions are satisfied, then the trivial representation of  $K_{\infty}^H$  appears in  $\rho_{m_1, n_1, m_2, n_2}$  exactly once.

**Proof.** Equation (50) holds by definition of  $\rho_{m_1, n_1, m_2, n_2}$  and because the Casimir operator acts as the scalar  $m(m + 2)$  on the irreducible representation of  $\mathfrak{sl}(2, \mathbb{C})$  of dimension  $m + 1$ . The complexification of the Lie algebra of  $K_{\infty}^H$  is given by  $\mathfrak{k}_{\mathbb{C}}^H = \langle U_1 + V_1, U_2 + V_2, P_+ + Q_+, P_- + Q_- \rangle$ . This Lie algebra is isomorphic to  $\mathfrak{gl}(2, \mathbb{C})$  and sits diagonally in the product of the two copies of  $\mathfrak{gl}(2, \mathbb{C})$  in (48). It follows that the restriction of the representation  $\rho_{m_1, n_1, m_2, n_2}$  to  $\mathfrak{k}_{\mathbb{C}}^H$  is given by  $\rho_{m_1, n_1} \otimes \rho_{m_2, n_2}$ , with each factor being a representation of  $\mathfrak{k}_{\mathbb{C}}^H \cong \mathfrak{gl}(2, \mathbb{C})$ . Such a tensor product contains the trivial representation (and then with multiplicity one) if and only if the second factor is the contragredient of the first, i.e., if and only if  $(m_2, n_2) = (m_1, -n_1)$ . ■

Let  $m$  be a non-negative integer, and  $l$  and  $l_2$  be any integers. Recall that  $l_2$  determines the extension of the central character of  $\tau$  to  $\mathbb{C}^{\times}$ . In our later applications  $l$  will indicate the scalar minimal  $K$ -type of a lowest weight representation of  $\mathrm{GSp}_4(\mathbb{R})$ , but for now  $l$  is just an integer. Let  $W_{m, l, l_2}^{\Delta}$  be the space of smooth,  $K_{\infty}^{G_2}$ -finite functions  $\Phi : K_{\infty}^{G_2} \rightarrow \mathbb{C}$  with the properties

$$\Phi(\hat{\zeta}_1 g) = \Phi(\hat{\zeta}_2 g) = \zeta^{l_2} \Phi(g) \quad \text{for } g \in K_{\infty}^{G_2}, \zeta \in S^1, \quad (51)$$

$$\Phi(gk) = \det(J(k, i_2))^{-l} \Phi(g) \quad \text{for } g \in K_{\infty}^{G_2}, k \in K_{\infty}^H, \quad (52)$$

$$\Delta_1 \Phi = \Delta_2 \Phi = m(m + 2)\Phi. \quad (53)$$

In (53), the Casimir elements  $\Delta_i$  are understood to act by right translation. As noted above, property (51) is required to extend  $\Phi$  to an element of  $I_{\Phi}(s, \chi, \chi_0, \tau)$ . Property (52) will become important when we evaluate local zeta integrals in Sect. 2.2. Imposing the additional condition (53) will result in a certain uniqueness which is useful for calculating intertwining operators; see Sect. 1.5. Evidently, the group consisting of all elements

$$\hat{r}(\theta) := m_2 \left( \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \right), \quad \theta \in \mathbb{R},$$

acts on  $W_{m,l,l_2}^\Delta$  by left translation. Let  $W_{m,l,l_2,l_1}^\Delta$  be the subspace of  $W_{m,l,l_2}^\Delta$  consisting of  $\Phi$  with the additional property

$$\Phi(\hat{r}(\theta)g) = e^{il_1\theta}\Phi(g) \quad \text{for } g \in G_2(\mathbb{R}), \theta \in \mathbb{R}. \quad (54)$$

Then

$$W_{m,l,l_2}^\Delta = \bigoplus_{l_1 \in \mathbb{Z}} W_{m,l,l_2,l_1}^\Delta. \quad (55)$$

Let  $D$  be the function on  $K_\infty^{G_2}$  given by  $D(g) = \det(J(g, i_2))$ . It is easily verified that

$$(U_1 - U_2)D = (V_1 - V_2)D = P_\pm D = Q_\pm D = 0.$$

Hence  $\Delta_i D = 0$  for  $i = 1, 2$ , and consequently  $\Delta_i(fD^l) = (\Delta_i f)D^l$  for any smooth function  $f$  on  $K_\infty^{G_2}$ . It is then easy to see that the map  $\Phi \mapsto \Phi D^l$  provides isomorphisms

$$W_{m,l,l_2}^\Delta \xrightarrow{\sim} W_{m,0,l_2+l}^\Delta \quad \text{and} \quad W_{m,l,l_2,l_1}^\Delta \xrightarrow{\sim} W_{m,0,l_2+l,l_1-l}^\Delta. \quad (56)$$

Let  $L^2(K_\infty^{G_2})_{\text{fin}}$  be the space of smooth,  $K_\infty^{G_2}$ -finite functions  $K_\infty^{G_2} \rightarrow \mathbb{C}$ . It is a module for  $K_\infty^{G_2} \times K_\infty^{G_2}$  via  $((g_1, g_2).f)(h) = f(g_1^{-1}hg_2)$ . By the Peter-Weyl theorem, as  $K_\infty^{G_2} \times K_\infty^{G_2}$ -modules,

$$L^2(K_\infty^{G_2})_{\text{fin}} \cong \bigoplus_{\rho} (\tilde{\rho} \otimes \rho) \quad (\text{algebraic direct sum}),$$

where  $\rho$  runs through all equivalence classes of irreducible representations of  $K_\infty^{G_2}$ , and where  $\tilde{\rho}$  denotes the contragredient. Evidently,

$$W_{m,0,l_2+l,l_1-l}^\Delta = \bigoplus_{\rho} (W_{m,0,l_2+l,l_1-l}^\Delta \cap (\tilde{\rho} \otimes \rho)), \quad (57)$$

and analogously for  $W_{m,0,l_2+l}^\Delta$ .

**1.3.2 Lemma.** *Let  $m$  be a non-negative integer, and  $l$  and  $l_2$  be any integers.*

i) *Let  $\rho = \rho_{m_1,n_1,m_2,n_2}$ . Then, for  $l_1 \in \mathbb{Z}$ ,*

$$\dim(W_{m,0,l_2+l,l_1-l}^\Delta \cap (\tilde{\rho} \otimes \rho)) = \begin{cases} 1 & \text{if } m_1 = m_2 = m, n_1 = l_2 + l, n_2 = -(l_2 + l), \\ & |l_1 - l| \leq m, l_1 - l \equiv l_2 + l \equiv m \pmod{2}, \\ 0 & \text{otherwise.} \end{cases}$$

ii) *For  $l_1 \in \mathbb{Z}$ ,*

$$\dim(W_{m,0,l_2+l,l_1-l}^\Delta) = \begin{cases} 1 & \text{if } |l_1 - l| \leq m, l_1 - l \equiv l_2 + l \equiv m \pmod{2}, \\ 0 & \text{otherwise.} \end{cases}$$

iii)

$$\dim(W_{m,l,l_2}^\Delta) = \begin{cases} m + 1 & \text{if } l_2 + l \equiv m \pmod{2}, \\ 0 & \text{otherwise.} \end{cases}$$

**Proof.** i) By the right  $K_\infty^H$ -invariance of functions in  $W_{m,0,l_1-l,l_2+l}^\Delta$  and Lemma 1.3.1 ii), if  $\tilde{\rho} \otimes \rho$  contributes to  $W_{m,0,l_2+l,l_1-l}^\Delta$ , then necessarily  $m_1 = m_2$  and  $n_1 = -n_2$ . Condition (53) forces  $m_1 = m_2 = m$ . Assume all of this is satisfied, say  $\rho = \rho_{m,n,m,-n}$ . Then, by Lemma 1.3.1 ii), there exists a non-zero vector  $v_0 \in \rho$ , unique up to multiples, such that  $v_0$  is fixed by  $K^H$ . Hence, any

element  $w \in W_{m,0,l_2+l,l_1-l}^\Delta \cap (\tilde{\rho} \otimes \rho)$  is of the form  $w = v \otimes v_0$  for some  $v \in \tilde{\rho} = \rho_{m,-n,m,n}$ . Taking into account that the first element of the center of  $\mathfrak{k}_\mathbb{C}$  in (49) acts trivially on  $W_{m,0,l_2+l,l_1-l}^\Delta$ , any element  $\Phi$  of this space has the following transformation properties under left translation  $L$ ,

$$L(U_1 - U_2)\Phi = (l_1 - l)\Phi, \quad L(V_1 - V_2)\Phi = (l_1 - l)\Phi, \quad (58)$$

$$L(U_1 + U_2)\Phi = -(l_2 + l)\Phi, \quad L(V_1 + V_2)\Phi = (l_2 + l)\Phi. \quad (59)$$

Since  $U_1 + U_2$  and  $V_1 + V_2$  are in the center, (59) implies that  $R(U_1 + U_2)\Phi = (l_2 + l)\Phi$  and  $R(V_1 + V_2)\Phi = -(l_2 + l)\Phi$ , where  $R$  is right translation. It follows that  $n = l_2 + l$ . This number must have the same parity as  $m$ . From (58) we conclude that  $v$  is a vector of weight  $(l_1 - l, l_1 - l)$  in  $\tilde{\rho}$ . There exists such a vector  $v$  in  $\tilde{\rho}$  if and only if  $-m \leq l_1 - l \leq m$  and  $l_1 - l \equiv m \pmod{2}$ , and in this case  $v$  is unique up to multiples.

ii) follows from i) and (57).

iii) For  $l = 0$  the statement follows from ii) and (55). For other values of  $l$ , it follows from the  $l = 0$  case and (56). ■

Our next task will be to find an explicit formula for the function spanning the one-dimensional space  $W_{m,l,l_2,l_1}^\Delta$ . We define, for  $g \in K_\infty^{G_2}$ ,

$$\begin{aligned} \hat{a}(g) &= (1, 1)\text{-coefficient of } J(g^t g, i_2), & \hat{b}(g) &= (1, 2)\text{-coefficient of } J(g^t g, i_2), \\ \hat{c}(g) &= (2, 1)\text{-coefficient of } J(g^t g, i_2), & \hat{d}(g) &= (2, 2)\text{-coefficient of } J(g^t g, i_2). \end{aligned}$$

Since they can be written in terms of matrix coefficients, these are  $K_\infty^{G_2}$ -finite functions. It is not difficult to calculate the action of  $P_\pm, Q_\pm$ , the torus elements and the Casimir elements on the functions  $\hat{a}, \hat{b}, \hat{c}, \hat{d}$  under left and right translation explicitly. The following lemma summarizes the results.

**1.3.3 Lemma.** *Let  $m$  be a non-negative integer.*

i) *If  $f = \hat{a}^{i_1} \hat{b}^{i_2} \hat{c}^{i_3} \hat{d}^{i_4}$  with non-negative integers  $i_1, \dots, i_4$  such that  $i_1 + i_2 + i_3 + i_4 = m$ , then, under right translation,*

$$\Delta_i f^m = m(m+2)f^m \quad \text{for } i = 1, 2.$$

ii) *The functions  $f$  as in i) are contained in  $\tilde{\rho} \otimes \rho$  with  $\rho = \rho_{m,m,m,-m}$  and are right invariant under  $K_\infty^H$ .*

iii) *Let  $f = \hat{b}^{m-j} \hat{c}^j$  with  $0 \leq j \leq m$ . Then, with  $L$  being left translation,*

$$L(U_1 - U_2)f = (m - 2j)f, \quad L(V_1 - V_2)f = (m - 2j)f, \quad (60)$$

$$L(U_1 + U_2)f = -mf, \quad L(V_1 + V_2)f = mf. \quad (61)$$

Using this lemma, it is easy to verify that the function

$$\hat{b}^{\frac{m+l_1-l}{2}} \hat{c}^{\frac{m-l_1+l}{2}} (\hat{a}\hat{d} - \hat{b}\hat{c})^{\frac{l_2+l-m}{2}}$$

lies in  $W_{m,0,l_2+l,l_1-l}^\Delta$ , provided all exponents are integers and the first two are non-negative. In view of (56), we obtain the following result.

**1.3.4 Proposition.** Let  $m$  be a non-negative integer, and  $l, l_1, l_2$  be any integers. We assume that  $|l_1 - l| \leq m$  and  $l_1 - l \equiv l_2 + l \pmod{2}$ , so that the space  $W_{m,l,l_2,l_1}^\Delta$  is one-dimensional. Then this space is spanned by the function

$$\Phi_{m,l,l_2,l_1}^\# := (-i)^m \hat{b}^{\frac{m+l_1-l}{2}} \hat{c}^{\frac{m-l_1+l}{2}} (\hat{a}\hat{d} - \hat{b}\hat{c})^{\frac{l_2+l-m}{2}} D^{-l}, \quad (62)$$

where  $D(g) = \det(J(g, i_2))$ . This function has the property that

$$\Phi_{m,l,l_2,l_1}^\#(\eta_0) = 1, \quad (63)$$

with  $\eta_0$  as in (6).

### Special vectors in $I(s, \chi, \chi_0, \tau)$

We return to the induced representation  $I_\Phi(s, \chi, \chi_0, \tau)$ , considered a subspace of the Borel induced representation  $I_\Phi(s, \chi, \chi_0, \beta_1 \times \beta_2)$ . Since the functions  $\Phi_{m,l,l_2,l_1}^\#$  defined in Proposition 1.3.4 satisfy condition (47), they extend to elements of  $I_\Phi(s, \chi, \chi_0, \beta_1 \times \beta_2)$ . We use the same notation for the extended functions.

**1.3.5 Lemma.** The function  $\Phi_{m,l,l_2,l_1}^\#$  belongs to  $I_\Phi(s, \chi, \chi_0, \tau)$  if and only if the weight  $l_1$  occurs in  $\tau$ .

**Proof.** As a subspace of  $I_\Phi(s, \chi, \chi_0, \beta_1 \times \beta_2)$ , the representation  $I_\Phi(s, \chi, \chi_0, \tau)$  consists of all functions  $\Phi : G_2 \rightarrow \mathbb{C}$  of the form

$$\Phi(m_1 m_2 n k) = \delta_P(m_1 m_2)^{s+1/2} \chi(m_1) \varphi(m_2) J(k), \quad m_i \in M_i(\mathbb{R}), n \in N(\mathbb{R}), k \in K_\infty^{G_2},$$

where  $\varphi$  lies in  $\chi_0 \times \tau$ , and where  $J$  is an appropriate function on  $K_\infty^{G_2}$ . It follows that  $\Phi \in I_\Phi(s, \chi, \chi_0, \beta_1 \times \beta_2)$  lies in  $I_\Phi(s, \chi, \chi_0, \tau)$  if and only if the function

$$M_2(\mathbb{R}) \ni m_2 \mapsto \Phi(m_2) \delta_P(m_2)^{-s-1/2}$$

belongs to  $\chi_0 \times \tau$ . Since  $\Phi_{m,l,l_2,l_1}^\#$  satisfies (54), the function  $m_2 \mapsto \Phi_{m,l,l_2,l_1}^\#(m_2)$  has weight  $l_1$ . The assertion follows. ■

For simplicity, we will from now on let  $\mathbf{c} = 1$  for the rest of this section; this is all we need for the global application. Let the classical Whittaker function  $W_{k,m}$  be the same as in [6, p. 244] or [39, 7.1.1]. We fix a point  $t^+ \in \mathbb{R}_{>0}$ , depending on  $p$ , such that

$$W_{\pm \frac{l_1}{2}, \frac{p}{2}}(t^+) \neq 0 \quad \text{for all } l_1 \in \mathbb{Z}. \quad (64)$$

Note that, if  $p$  is a positive integer (corresponding to  $\tau$  being a discrete series representation), we can choose  $t^+ = 1$ , since  $W_{\pm \frac{l_1}{2}, \frac{p}{2}}$  is essentially an exponential function. Let  $W_{l_1}$  be the vector of weight  $l_1$  in the  $\psi^{-1}$  Whittaker model of  $\tau$ . Using differential operators and solving differential equations, one can show that there exist constants  $a^+, a^- \in \mathbb{C}$  such that

$$W_{l_1} \left( \begin{bmatrix} t & 0 \\ 0 & 1 \end{bmatrix} \right) = \begin{cases} a^+ \omega_\tau((4\pi t)^{1/2}) W_{\frac{l_1}{2}, \frac{p}{2}}(4\pi t) & \text{if } t > 0, \\ a^- \omega_\tau((-4\pi t)^{1/2}) W_{-\frac{l_1}{2}, \frac{p}{2}}(-4\pi t) & \text{if } t < 0. \end{cases} \quad (65)$$

Our choice of additive character implies that  $a^+$  is non-zero as long as  $l_1 > 0$ . We will normalize the constant  $a^+ = a_{l_1,p,q}^+$  such that

$$W_{l_1}\left(\begin{bmatrix} t^+ & \\ & 1 \end{bmatrix}\right) = 1.$$

i.e.,

$$a^+ = a_{l_1,p,q}^+ = (\omega_\tau((4\pi t^+)^{1/2}) W_{\frac{l_1}{2}, \frac{p}{2}}(4\pi t^+))^{-1} = (4\pi t^+)^{-q/2} W_{\frac{l_1}{2}, \frac{p}{2}}(4\pi t^+)^{-1}. \quad (66)$$

Consider the Whittaker realization  $I_W(s, \chi, \chi_0, \tau)$  of  $I(s, \chi, \chi_0, \tau)$ , with  $\tau$  given in its  $\psi^{-1}$  Whittaker model (see (24), (25)). We extend  $W_{l_1}$  to a function on  $G_1(\mathbb{R})$  via the character  $\chi_0$ ; see (22). Using the Iwasawa decomposition, we define a function  $W_{m,l,l_2,l_1}^\#$  in  $I_W(s, \chi, \chi_0, \tau)$  by

$$W_{m,l,l_2,l_1}^\#(m_1 m_2 n k, s) = (t^+)^{q/2} \delta_P^{s+1/2}(m_1 m_2) \chi(m_1) W_{l_1}(m_2) \Phi_{m,l,l_2,l_1}^\#(k), \quad (67)$$

where  $m_1 \in M^{(1)}(\mathbb{R})$ ,  $m_2 \in M^{(2)}(\mathbb{R})$ ,  $n \in N(\mathbb{R})$  and  $k \in K_\infty^{G_2}$ , and where  $\Phi_{m,l,l_2,l_1}^\#$  is the same function as in (62); this is well-defined by the transformation properties of  $W_{l_1}$  and  $\Phi_{m,l,l_2,l_1}^\#$ . Note that

$$W_{m,l,l_2,l_1}^\#(\text{diag}(\sqrt{t^+}, t^+, \sqrt{t^+}, 1) \eta_0, s) = 1.$$

There is an intertwining operator  $\Phi \mapsto W_\Phi$  from  $I_\Phi(s, \chi, \chi_0, \tau)$  to  $I_W(s, \chi, \chi_0, \tau)$ , which, in the region of convergence, is given by

$$W_\Phi(g) = \int_{\mathbb{R}} e^{-2\pi i x} \Phi\left(\begin{bmatrix} 1 & & 1 \\ & 1 & \\ -1 & & 1 \end{bmatrix} \begin{bmatrix} 1 & & x \\ & 1 & \\ & & 1 \end{bmatrix} g\right) dx. \quad (68)$$

Outside the region of convergence the intertwining operator is given by the analytic continuation of this integral. This operator is simply an extension of a standard intertwining operator for the underlying  $\text{GL}_2(\mathbb{R})$  representation  $\beta_1 \times \beta_2$ . It is easy to see that under this intertwining operator the function  $\Phi_{m,l,l_2,l_1}^\#$  maps to a multiple of  $W_{m,l,l_2,l_1}^\#$ . Let  $\kappa_{l_1,p,q}$  be the constant such that

$$W_{\Phi_{m,l,l_2,l_1}^\#} = \kappa_{l_1,p,q} W_{m,l,l_2,l_1}^\# \quad (69)$$

We will distinguish three disjoint cases A, B, C according to the type of  $\tau$  and the constellation of its weights relative to the integer  $l$  (which later will be a minimal  $\text{GSp}_4$  weight).

- **Case A:** Neither the weight  $l$  nor the weight  $l-1$  occur in  $\tau$ .
- **Case B:** The weight  $l$  occurs in  $\tau$ .
- **Case C:** The weight  $l-1$  occurs in  $\tau$ .

Note that in Case A necessarily  $\tau = \mathcal{D}_{p,q/2}$ , a discrete series representation with Harish-Chandra parameter  $p \geq l$  (and central character satisfying  $a \mapsto a^q$  for  $a > 0$ ). In this case let us set  $l_1 = p+1$ , which is the minimal weight. It satisfies  $l_1 \geq 2$ . In each of the three cases we will define a non-negative integer  $m$  and a distinguished function  $\Phi^\#$  as a linear combination of certain  $\Phi_{m,l,l_2,l_1}^\#$  as in (62). The definition is as in the following table. The last column of the table shows  $W^\#$ , by

definition the image of  $\Phi^\#$  under the intertwining operator  $\Phi \mapsto W_\Phi$ .

Case	$m$	$\Phi^\#$	$W^\#$
A	$l_1 - l$	$\Phi_{m,l,l_2,l_1}^\#$	$\kappa_{l_1,p,q} W_{m,l,l_2,l_1}^\#$
B	0	$\Phi_{m,l,l_2,l}^\#$	$\kappa_{l,p,q} W_{m,l,l_2,l}^\#$
C	1	$\Phi_{m,l,l_2,l+1}^\# + (3s - \frac{p+q}{2})\Phi_{m,l,l_2,l-1}^\#$	$\kappa_{l+1,p,q} W_{m,l,l_2,l+1}^\# + (3s - \frac{p+q}{2})\kappa_{l-1,p,q} W_{m,l,l_2,l-1}^\#$

In all cases, by Lemma 1.3.5, the function  $\Phi^\#$  lies in  $I_\Phi(s, \chi, \chi_0, \tau)$ .

**1.3.6 Theorem.** Let  $(\tau, V_\tau)$  be a generic, irreducible, admissible representation of  $\mathrm{GL}_2(\mathbb{R})$  with central character  $\omega_\tau$ . We realize  $\tau$  as a subrepresentation of an induced representation  $\beta_1 \times \beta_2$ , and define  $p, q \in \mathbb{C}$  by (46). Let  $l_2$  be an integer of the same parity as the weights of  $\tau$ . Let  $\chi_0$  be the character of  $\mathbb{C}^\times$  such that  $\chi_0|_{\mathbb{R}^\times} = \omega_\tau$  and  $\chi_0(\zeta) = \zeta^{l_2}$  for  $\zeta \in S^1$ , and let  $\chi$  be the character of  $\mathbb{C}^\times$  defined by (45). Assume that  $l$  is a positive integer. Let  $m$  and  $\Phi^\#$  be chosen according to table (71).

i) The function  $\Phi^\#$  satisfies

$$\Phi^\#(gk) = \det(J(k, i_2))^{-l} \Phi^\#(g) \quad \text{for } g \in G_2(\mathbb{R}), k \in K_\infty^H \quad (72)$$

and

$$\Delta_1 \Phi^\# = \Delta_2 \Phi^\# = m(m+2) \Phi^\#. \quad (73)$$

- ii) Assume we are in Case A or B. Then, up to scalars,  $\Phi^\#$  is the unique  $K_\infty^{G_2}$ -finite element of  $I_\Phi(s, \chi, \chi_0, \tau)$  with the properties (72) and (73).
- iii) Assume we are in Case C. Then the space of  $K_\infty^{G_2}$ -finite functions in  $I_\Phi(s, \chi, \chi_0, \tau)$  with the properties (72) and (73) is two-dimensional, spanned by  $\Phi_{m,l,l_2,l-1}^\#$  and  $\Phi_{m,l,l_2,l+1}^\#$ .

**Proof.** i) is obvious, since  $\Phi^\#$  lies in  $W_{m,l,l_2}^\Delta$ .

ii) Assume first we are in Case A. By our hypotheses,  $0 < l < l_1$ . Assume that  $\Phi \in I_\Phi(s, \chi, \chi_0, \tau)$  is  $K_\infty^{G_2}$ -finite and satisfies (72) and (73). Then, evidently, the restriction of  $\Phi$  to  $K_\infty^{G_2}$  lies in  $W_{m,l,l_2}^\Delta$ . By (55) and Proposition 1.3.4,

$$W_{m,l,l_2}^\Delta = \bigoplus_{\substack{j \in \mathbb{Z} \\ |j-l| \leq m \\ j-l \equiv m \pmod{2}}} \mathbb{C} \Phi_{m,l,l_2,j}^\#.$$

If a  $\Phi_{m,l,l_2,j}^\#$  occurring in this direct sum is an element of  $I_\Phi(s, \chi, \chi_0, \tau)$ , then, by Lemma 1.3.5, the weight  $j$  occurs in  $\tau$ . Since  $\tau$  has minimal weight  $l_1$ , this implies  $j \leq -l_1$  or  $j \geq l_1$ . The first inequality leads to a contradiction, and the second inequality implies  $j = l_1$ . This proves the uniqueness in Case A. In Case B, as before, the restriction of any  $K_\infty^{G_2}$ -finite  $\Phi \in I_\Phi(s, \chi, \chi_0, \tau)$  satisfying (72) and (73) to  $K_\infty^{G_2}$  lies in  $W_{m,l,l_2}^\Delta$ . By Lemma 1.3.2, this space is one-dimensional.

iii) Again, the restriction of any  $K_\infty^{G_2}$ -finite  $\Phi \in I_\Phi(s, \chi, \chi_0, \tau)$  satisfying (72) and (73) to  $K_\infty^{G_2}$  lies in  $W_{m,l,l_2}^\Delta$ . By Lemma 1.3.2, this space is two-dimensional.  $\blacksquare$

Since the functions  $\Phi^\#$  and  $W^\#$  have the same right transformation properties, the following is an immediate consequence of Theorem 1.3.6.

**1.3.7 Corollary.** *Let the non-negative integer  $m$  and the function  $W^\#$  in  $I_W(s, \chi, \chi_0, \tau)$  be chosen according to table (71).*

i) *The function  $W^\#$  satisfies*

$$W^\#(gk) = \det(J(k, i_2))^{-l} W^\#(g) \quad \text{for } g \in G_2(\mathbb{R}), k \in K_\infty^H \quad (74)$$

and

$$\Delta_1 W^\# = \Delta_2 W^\# = m(m+2)W^\#. \quad (75)$$

ii) *Assume we are in Case A or B. Then, up to scalars,  $W^\#$  is the unique  $K_\infty^{G_2}$ -finite element of  $I_W(s, \chi, \chi_0, \tau)$  with the properties (74) and (75).*

iii) *Assume we are in Case C. Then the space of  $K_\infty^{G_2}$ -finite functions in  $I_W(s, \chi, \chi_0, \tau)$  with the properties (74) and (75) is two-dimensional, spanned by  $W_{m,l,l_2,l-1}^\#$  and  $W_{m,l,l_2,l+1}^\#$ .*

### A relation between unknown constants

In this section we defined the constants  $\kappa_{l_1,p,q}$  and  $a_{l_1,p,q}^+$ ; see (69) and (66). Note that these constants also depend on the choice of the point  $t^+$ , which is not reflected in the notation. We do not know the explicit value of any of these constants. However, the following lemma describes a relation between these constants which will become important in the proof of Lemma 2.4.2.

**1.3.8 Lemma.** *Let  $\beta_1$  and  $\beta_2$  be characters of  $\mathbb{R}^\times$  such that the induced representation  $\beta_1 \times \beta_2$  is irreducible. Let  $p, q \in \mathbb{C}$  be as in (46). Then, for any integer  $l$  whose parity is different from the parity of the weights of  $\beta_1 \times \beta_2$ ,*

$$\frac{\kappa_{l-1,p,q} a_{l-1,p,q}^+}{\kappa_{l+1,p,q} a_{l+1,p,q}^+} = -\frac{1}{2}(p+l). \quad (76)$$

**Proof.** We consider the intertwining operator  $\varphi \mapsto W_\varphi$  from  $\tau$  to the Whittaker model  $\mathcal{W}(\beta_1 \times \beta_2, \psi^{-c})$  which, in the region of convergence, is given by

$$W_\varphi(g) = \int_{\mathbb{R}} e^{-2\pi ix} \varphi \left( \begin{bmatrix} 1 & \\ -1 & \end{bmatrix} \begin{bmatrix} 1 & x \\ & 1 \end{bmatrix} g \right) dx. \quad (77)$$

For a weight  $k$  occurring in  $\beta_1 \times \beta_2$  let  $\varphi_k$  be the element of  $\beta_1 \times \beta_2$  of weight  $k$  satisfying  $\varphi_k(1) = 1$ , and let  $W_k$  be the element of  $\mathcal{W}(\beta_1 \times \beta_2, \psi^{-1})$  of weight  $k$  satisfying  $W_k \left( \begin{bmatrix} t^+ & \\ & 1 \end{bmatrix} \right) = 1$ . Then  $W_{\varphi_k} = \kappa_{k,p,q}(t^+)^{q/2} W_k$  with the same  $\kappa_{k,p,q}$  as in (69).

Recall that the constants  $a_{k,p,q}^+$  defined in (66) were designed so that

$$w_k(t) := W_k \left( \begin{bmatrix} t & \\ & 1 \end{bmatrix} \right) = a_{k,p,q}^+ (4\pi t)^{q/2} W_{\frac{k}{2}, \frac{p}{2}}(4\pi t) \quad (78)$$

satisfies  $w_k(t^+) = 1$ . If  $L$  denotes the Lie algebra element  $\frac{1}{2} \begin{bmatrix} 1 & -i \\ -i & -1 \end{bmatrix}$ , then straightforward calculations show that

$$\tau(L)\varphi_k = \frac{p+1-k}{2}\varphi_{k-2}, \quad (\tau(L)W_k)(\begin{bmatrix} t \\ 1 \end{bmatrix}) = \left( -\frac{q}{2} - \frac{k}{2} + 2\pi t \right) w_k(t) + tw'_k(t) \quad (79)$$

(where  $\tau$  stands for the right translation action on both  $\beta_1 \times \beta_2$  and its Whittaker model). For  $k$  one of the weights appearing in  $\beta_1 \times \beta_2$ , define constants  $\lambda_{k,p,q}$  and  $\mu_{k,p,q}$  by

$$\tau(L)\varphi_k = \lambda_{k,p,q} \varphi_{k-2} \quad \text{and} \quad \tau(L)W_k = \mu_{k,p,q} W_{k-2}.$$

By our normalizations,  $\lambda_{k,p,q} = (\tau(L)\varphi_k)(1)$  and  $\mu_{k,p,q} = (\tau(L)W_k)(\begin{bmatrix} t^+ \\ 1 \end{bmatrix})$ . Hence, by (79),

$$\lambda_{k,p,q} = \frac{p+1-k}{2}, \quad \mu_{k,p,q} = -\frac{q}{2} - \frac{k}{2} + 2\pi t^+ + t^+ w'_k(t^+). \quad (80)$$

Following the function  $\varphi_k$  through the commutative diagram

$$\begin{array}{ccc} \beta_1 \times \beta_2 & \xrightarrow{\tau(L)} & \beta_1 \times \beta_2 \\ \downarrow & & \downarrow \\ \mathcal{W}(\tau, \psi^{-1}) & \xrightarrow[\tau(L)]{} & \mathcal{W}(\tau, \psi^{-1}) \end{array}$$

we get the identity

$$\kappa_{k,p,q} \mu_{k,p,q} = \lambda_{k,p,q} \kappa_{k-2,p,q}. \quad (81)$$

To further calculate the constant  $\mu_{k,p,q}$ , we will take the derivative of the function  $w_k$  defined in (78). We will make use of the following identity for Whittaker functions,

$$z W'_{k,b}(z) = \left( k - \frac{z}{2} \right) W_{k,b}(z) - \left( b^2 - \left( k - \frac{1}{2} \right)^2 \right) W_{k-1,b}(z) \quad (82)$$

(see [39, 7.2.1]). Using this, one obtains from (66), (78) and (80) that

$$\mu_{k,p,q} = -\frac{p^2 - (k-1)^2}{4} \frac{a_{k,p,q}^+}{a_{k-2,p,q}^+}.$$

Substituting the values of  $\lambda_{k,p,q}$  and  $\mu_{k,p,q}$  into (81) and setting  $k = l+1$  proves the asserted identity. ■

## 1.4 Intertwining operator: non-archimedean case

In this section let  $F$  be  $p$ -adic. We use the notation from Theorem 1.2.3. In addition, we will assume that  $\Lambda|_{F^\times} = 1$ ; this will be sufficient for our global applications. In this section we will calculate the function  $K(s)$  given in (31).

Let us be precise about the measure on  $N(F)$ . Recall that  $N(F)$  consists of one copy of  $F$  and two copies of  $L$ . The measure on  $F$  is the one that is self-dual with respect to the character  $\psi$ , and

the measure on  $L$  is the one that is self-dual with respect to the character  $\psi \circ \text{tr}_{L/F}$ . Since we are assuming that  $\psi$  has conductor  $\mathfrak{o}$ , it follows (see Sect. 2.2 of [61]) that

$$\text{vol}(\mathfrak{o}) = 1 \quad \text{and} \quad \text{vol}(\mathfrak{o}_L) = N(\mathbf{d})^{-1/2}. \quad (83)$$

Recall here that the norm of the different is the discriminant, and that  $\mathbf{d} = \mathbf{b}^2 - 4\mathbf{a}\mathbf{c}$  generates the discriminant of  $L/F$  by our conventions. If we let  $\mathbf{d}\mathfrak{o} = \varpi^\delta \mathfrak{o}$  (where  $\delta = 0$  unless  $L/F$  is a ramified field extension), then  $\text{vol}(\mathfrak{o}_L) = q^{-\delta/2}$ . This explains the factor  $q^{-\delta}$  in the following result.

**1.4.1 Proposition. (Gindikin-Karpelevich Formula)** *Let  $\delta$  be the valuation of the discriminant of  $L/F$  if  $L/F$  is a ramified field extension, and  $\delta = 0$  otherwise. If  $\tau$  is unramified, then*

$$K(s) = q^{-\delta} \frac{L(6s, \chi|_{F^\times}) L(3s, \tau \times \mathcal{A}\mathcal{I}(\Lambda) \times \chi|_{F^\times})}{L(6s + 1, \chi|_{F^\times}) L(3s + 1, \tau \times \mathcal{A}\mathcal{I}(\Lambda) \times \chi|_{F^\times})}.$$

This formula can be obtained by a straightforward integral calculation; we omit the details. For non-spherical  $\tau$  it will be necessary to distinguish the inert, split and ramified cases. For our global applications it turns out that explicit knowledge of  $K(s)$  at finitely many finite places is not necessary. Thus, we will only calculate  $K(s)$  in the inert and split cases.

We will first assume that  $L/F$  is an unramified field extension. We write the explicit formula (32) as  $I_1 + I_2$ , where in  $I_1$  the  $z$ -integration is restricted to the set  $\mathfrak{o}_L$ , and in  $I_2$  the  $z$ -integration is restricted to  $L \setminus \mathfrak{o}_L$ . After some changes of variables, we get

$$I_1 = \int_{\mathfrak{o}_L} \int_L \int_F W^\# \left( \begin{bmatrix} 1 & & \\ y & 1 & \\ x & & 1 & -\bar{y} \\ & & 1 & \\ & & & 1 \end{bmatrix} w_1 \begin{bmatrix} 1 & z & & \\ & 1 & & \\ & & 1 & \\ & & & -\bar{z} & 1 \end{bmatrix} \eta, s \right) dz dy dx \quad (84)$$

and

$$I_2 = \int_{L \setminus \mathfrak{o}_L} \int_L \int_F |z\bar{z}| W^\# \left( \begin{bmatrix} \bar{z}^{-1} & & 1 & \\ & z^{-1} & 1 & \\ & & z & \\ & & & \bar{z} \end{bmatrix} \begin{bmatrix} 1 & & & \\ & 1 & & xz\bar{z} - \bar{y}z - y\bar{z} \\ & & 1 & \\ & & & 1 \end{bmatrix} \right. \\ \left. \times \begin{bmatrix} 1 & & & \\ y & 1 & & \\ x & & 1 & -\bar{y} \\ & & & 1 \end{bmatrix} \begin{bmatrix} -1 & & 1 & \\ & -1 & & \\ & & -1 & \end{bmatrix} \begin{bmatrix} 1 & & & \\ z^{-1} & 1 & & \\ & & 1 & -\bar{z}^{-1} \\ & & & 1 \end{bmatrix} \eta, s \right) dx dy dz. \quad (85)$$

The argument of  $W^\#$  needs to be written as  $pk$ , where  $p \in P(F)$  and  $k \in K^{G_2}$ . For both  $I_1$  and  $I_2$

the key is decomposing the matrix  $g = \begin{bmatrix} 1 & & & \\ y & 1 & & \\ x & & 1 & -\bar{y} \\ & & & 1 \end{bmatrix}$  in this way. There are five cases depending

on the values of  $x$  and  $y$ . For instance, if  $x \in \mathfrak{o}, y \in \mathfrak{o}_L$  then  $g$  already lies in  $K^{G_2}$ . On the other hand if  $x \in \mathfrak{o}, y \notin \mathfrak{o}_L$  then

$$g = \begin{bmatrix} -y^{-1} & -1 & & \\ & -y & & \\ & & -\bar{y} & \\ & & & 1 \end{bmatrix} \begin{bmatrix} & & 1 & \\ -1 & & -y^{-1} & \\ -x\bar{y}^{-1} & & -\bar{y}^{-1} & \\ -x & & -1 & \end{bmatrix}. \quad (86)$$

Similar matrix identities (which we omit for reasons of brevity) exist in the three remaining cases

$$x \notin \mathfrak{o}, y \in \mathfrak{o}_L, \quad x \notin \mathfrak{o}, y \notin \mathfrak{o}_L, yx^{-1} \in \mathfrak{o}_L, \quad x \notin \mathfrak{o}, y \notin \mathfrak{o}_L, yx^{-1} \notin \mathfrak{o}_L.$$

We now have ten cases, five for  $z \in \mathfrak{o}_L$  and five for  $z \in L \setminus \mathfrak{o}_L$ . In each case let  $k$  denote the  $K^{G_2}$  component of the argument of  $W^\#$ . Using the fact that  $W^\#$  is supported on  $P(F)\eta_0 K^H \Gamma(\mathfrak{P}^n)$  gives the following conditions on  $k$ . The notation is such that  $y = y_1 + \alpha y_2$  and  $z = z_1 + \alpha z_2$  with  $y_1, y_2, z_1, z_2 \in \mathfrak{o}$ .

case	$x$	$y$	$z$	$yx^{-1}$	condition for $k$ to be in the support of $W^\#$
i)	$\in \mathfrak{o}$	$\in \mathfrak{o}_L$	$\in \mathfrak{o}_L$		$y_2 + (x + yz + \bar{y}\bar{z}) \in \mathfrak{o}^\times$ or $z_2 - z\bar{z} \in \mathfrak{o}^\times$
ii)	$\in \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\in \mathfrak{o}_L$		$z_2 - z\bar{z} \in \mathfrak{o}^\times$
iii)	$\notin \mathfrak{o}$	$\in \mathfrak{o}_L$	$\in \mathfrak{o}_L$		always
iv)	$\notin \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\in \mathfrak{o}_L$	$\in \mathfrak{o}_L$	$\frac{y_2}{x} - \frac{y\bar{y}}{x^2} z_2 + \left(\frac{x+yz}{x}\right) \left(\frac{x+\bar{y}\bar{z}}{x}\right) \in \mathfrak{o}^\times$
v)	$\notin \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\in \mathfrak{o}_L$	$\notin \mathfrak{o}_L$	$\frac{1}{\alpha-\bar{\alpha}} \left(\frac{x}{y} - \frac{x}{\bar{y}}\right) - z_2 + \left(\frac{x}{y} + z\right) \left(\frac{x}{y} + \bar{z}\right) \in \mathfrak{o}^\times$
vi)	$\in \mathfrak{o}$	$\in \mathfrak{o}_L$	$\notin \mathfrak{o}_L$		always
vii)	$\in \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\notin \mathfrak{o}_L$		always
viii)	$\notin \mathfrak{o}$	$\in \mathfrak{o}_L$	$\notin \mathfrak{o}_L$		never
ix)	$\notin \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\notin \mathfrak{o}_L$	$\in \mathfrak{o}_L$	$\frac{y\bar{y}}{x^2} + \frac{y_2}{x} \in \mathfrak{o}^\times$
x)	$\notin \mathfrak{o}$	$\notin \mathfrak{o}_L$	$\notin \mathfrak{o}_L$	$\notin \mathfrak{o}_L$	always

According to these cases,  $K(s)$  is the sum of ten integrals  $I_i, \dots, I_x$ . By the support conditions,  $I_{viii} = 0$ . We split the first case up into i)a, the case where  $z_2 - z\bar{z} \in \mathfrak{o}^\times$ , and i)b, the case where  $z_2 - z\bar{z} \in \mathfrak{p}$  and  $y_2 + (x + yz + \bar{y}\bar{z}) \in \mathfrak{o}^\times$ . To evaluate the function  $W^\#$  in  $I_1$  and  $I_2$ , we will write the argument of  $W^\#$  as  $p\eta\kappa$  with  $p \in P(F)$  and  $\kappa \in K^H$ . Only the  $p$  part is important for the evaluation. Once the argument of  $W^\#$  is written as  $p\eta\kappa$ , it is straightforward to perform an initial evaluation of the integrals. We list only the results.

$$\begin{aligned}
I_{i)a} &= \left( \int_{\substack{\mathfrak{o}_L \\ z_2 - z\bar{z} \in \mathfrak{o}^\times}} \chi_0(z_2 - z\bar{z}) dz \right) W^{(0)} \left( \begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) \\
I_{i)b} &= \int_{\substack{\mathfrak{o}_L \\ z_2 - z\bar{z} \in \mathfrak{p}}} \int_{\mathfrak{o}^\times} W^{(0)} \left( \begin{bmatrix} x \\ 1 \end{bmatrix} \begin{bmatrix} 1 \\ z_2 - z\bar{z} \end{bmatrix} \right) dx dz \\
I_{ii)} &= \int_{\substack{\mathfrak{o}_L \\ z_2 - z\bar{z} \in \mathfrak{o}^\times}} \int_{L \setminus \mathfrak{o}_L} |y|_L^{-3(s+\frac{1}{2})} \chi \left( \frac{1}{z_2 - z\bar{z}} \right) \Lambda(\bar{y}) W^{(0)} \left( \begin{bmatrix} y\bar{y} & y_2 + yz + \bar{y}\bar{z} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right) dy dz \\
I_{iii)} &= \int_{\mathfrak{o}_L} \int_{\mathfrak{o}_L} \int_{F \setminus \mathfrak{o}} |x|^{-6(s+\frac{1}{2})} \chi(x^{-1}) W^{(0)} \left( \begin{bmatrix} \frac{y_2 + x + yz + \bar{y}\bar{z}}{x} & \\ & 1 \end{bmatrix} \begin{bmatrix} 1 \\ \frac{z_2 - z\bar{z}}{x} \end{bmatrix} \right) dx dy dz \\
I_{iv)} &= \int_{\mathfrak{o}_L} \int_{\mathfrak{o}_L} \int_{\substack{F \setminus \mathfrak{o} \\ u \in \mathfrak{o}^\times \\ yx \notin \mathfrak{o}_L}} |x|^{-6s-1} \chi(x^{-1}) \\
&\quad W^{(0)} \left( \begin{bmatrix} 1 & y\bar{y}x \\ 1 & 1 \end{bmatrix} \begin{bmatrix} y_2 - y\bar{y}z_2 + (1+yz)(1+\bar{y}\bar{z}) & \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ \frac{z_2 - z\bar{z}}{x} \end{bmatrix} \right) dx dy dz \\
I_{v)} &= \int_{\substack{\mathfrak{o}_L \\ z_2 - z\bar{z} \in \mathfrak{o}^\times}} \int_{L \setminus \mathfrak{o}_L} \int_{F \setminus \mathfrak{o}} |x|^{-6s-1} \chi(x^{-1}) |y|_L^{-3(s+\frac{1}{2})} \Lambda(\bar{y})
\end{aligned}$$

$$\begin{aligned}
& W^{(0)} \left( \begin{bmatrix} 1 & y\bar{y}x \\ & 1 \end{bmatrix} \begin{bmatrix} y_2 - y\bar{y}z_2 + (1+yz)(1+\bar{y}\bar{z}) & 1 \\ & 1 \end{bmatrix} \begin{bmatrix} 1 & \\ \frac{z_2-z\bar{z}}{x} & 1 \end{bmatrix} \right) dx dy dz \\
I_{vi)} &= \int_{L \setminus \mathfrak{o}_L} |z|_L^{-3s-\frac{1}{2}} \Lambda(z) W^{(0)} \left( \begin{bmatrix} 1 & \\ z\bar{z}(1-\frac{z_2}{z\bar{z}}) & \end{bmatrix} \begin{bmatrix} & 1 \\ -1 & \end{bmatrix} \right) dz \\
I_{vii)} &= \int_{L \setminus \mathfrak{o}_L} \int_{L \setminus \mathfrak{o}_L} |y|_L^{-3(s+\frac{1}{2})} |z|_L^{-3s-\frac{1}{2}} \Lambda(\bar{y}z) \\
&\quad \psi^{-\mathbf{c}} \left( -\frac{y}{z} - \frac{\bar{y}}{\bar{z}} + \frac{y_2}{z_2 - z\bar{z}} \right) W^{(0)} \left( \begin{bmatrix} y\bar{y} & \\ z\bar{z} & \end{bmatrix} \begin{bmatrix} 1 & \\ \frac{z_2-z\bar{z}}{z\bar{z}} & 1 \end{bmatrix} \begin{bmatrix} & 1 \\ -1 & \end{bmatrix} \right) dy dz \\
I_{ix)} &= \int_{L \setminus \mathfrak{o}_L} \int_{\mathfrak{o}_L^\times} \int_{F \setminus \mathfrak{o}} |z|_L^{-3s-\frac{1}{2}} \Lambda(z) |x|^{-6s-1} \chi(-x^{-1}) \psi^{-\mathbf{c}} \left( \frac{x(y\bar{y} + z\bar{z} + \bar{y}z + y\bar{z})}{z\bar{z}} \right) \\
&\quad W^{(0)} \left( \begin{bmatrix} 1 & \\ z\bar{z} & \end{bmatrix} \begin{bmatrix} y_2 - y\bar{y} + \frac{y\bar{y}z_2}{z\bar{z}} & 1 \\ & 1 \end{bmatrix} \begin{bmatrix} 1 & \\ -\frac{z_2-z\bar{z}}{xz\bar{z}} & 1 \end{bmatrix} \right) dx dy dz \\
I_x) &= \int_{L \setminus \mathfrak{o}_L} \int_{L \setminus \mathfrak{o}_L} \int_{F \setminus \mathfrak{o}} |y|_L^{-3(s+\frac{1}{2})} |z|_L^{-3s-\frac{1}{2}} \Lambda(\bar{y}z) |x|^{-6s-1} \chi_0(x) \\
&\quad W^{(0)} \left( \begin{bmatrix} 1 & \\ z\bar{z} & \end{bmatrix} \begin{bmatrix} 1 & x(y\bar{y} + z\bar{z} - \bar{y}z - y\bar{z}) \\ & 1 \end{bmatrix} \begin{bmatrix} y\bar{y}(1 + \frac{y_2}{y\bar{y}} - \frac{z_2}{z\bar{z}}) & 1 \\ & 1 \end{bmatrix} \begin{bmatrix} 1 & \\ \frac{z_2-z\bar{z}}{xz\bar{z}} & 1 \end{bmatrix} \right) dx dy dz.
\end{aligned}$$

These integrals can be calculated further, using standard  $p$ -adic techniques and known properties of the  $\mathrm{GL}_2$  Whittaker function  $W^{(0)}$ . We will omit the details of the calculation for reasons of brevity.

The calculations for the split case (when  $L = F \oplus F$ ) are similar. In this case the explicit formula (32) gives us an integral over five  $F$ -variables (coming from the two  $L$ -variables and one  $F$ -variable). Also, note that in the split case, we have the isomorphism

$$\begin{aligned}
\mathrm{GU}(2, 2; F \oplus F) &\cong \mathrm{GL}_4(F) \times \mathrm{GL}_1(F) \\
g &:= (g_1, g_2) \rightarrow (g_1, \mu(g)).
\end{aligned}$$

Using this, we can break up the integral (32) into several smaller integrals, which we evaluate in a manner similar to the inert case. After all the integrals are computed and combined, one obtains the following result, which is true in the inert as well as the split case.

**1.4.2 Theorem.** *Let  $(\tau, V_\tau)$  be an irreducible, admissible, generic representation of  $\mathrm{GL}_2(F)$ . Assume that  $L/F$  is either an unramified field extension or  $L = F \oplus F$ . Assume also that the conductor  $\mathfrak{p}^n$  of  $\tau$  satisfies  $n \geq 1$ . Let the character  $\chi_0$  of  $L^\times$  be such that  $\chi_0|_{F^\times} = \omega_\tau$  and  $\chi_0((1 + \mathfrak{P}^n) \cap \mathfrak{o}_L^\times) = 1$ . Let  $\Lambda$  be an unramified character of  $L^\times$  such that  $\Lambda|_{F^\times} = 1$ . Let the character  $\chi$  of  $L^\times$  be defined by (33). Let  $W^\#(\cdot, s)$  be the distinguished function in  $I(s, \chi, \chi_0, \tau)$  from Corollary 1.2.4, normalized such that  $W^\#(\eta_0, s) = 1$ . Then the function  $K(s)$  defined by (30) is given by*

$$K(s) = \chi_{L/F}(\varpi)^n \omega_\tau(\mathbf{c}^2/\mathbf{d}) \frac{\varepsilon(3s+1, \tilde{\tau}, \psi^{-\mathbf{c}})^2}{\varepsilon(6s, \omega_\tau^{-1}, \psi^{-\mathbf{c}})} \frac{L(6s, \chi|_{F^\times}) L(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})}{L(1-6s, \chi^{-1}|_{F^\times}) L(3s+1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})}.$$

## 1.5 Intertwining operator: archimedean case

In this section let  $F = \mathbb{R}$ . We use the notation and setup from Sect. 1.3. Hence,  $(\tau, V_\tau)$  is an irreducible, admissible, generic representation of  $\mathrm{GL}_2(\mathbb{R})$ , and  $l_2 \in \mathbb{Z}$  has the same parity as the weights of  $\tau$ . The character  $\chi_0$  of  $\mathbb{C}^\times$  is such that  $\chi_0|_{\mathbb{R}^\times} = \omega_\tau$  and  $\chi_0(\zeta) = \zeta^{l_2}$  for  $\zeta \in \mathbb{C}^\times$ ,  $|\zeta| = 1$ , and  $\chi(\zeta) = \chi_0(\bar{\zeta})^{-1}$ . We realize  $\tau$  as a subrepresentation of some  $\beta_1 \times \beta_2$ , and the quantities  $p, q$  are defined by (46). Let  $W^\#$  be the distinguished function in  $I_W(s, \chi, \chi_0, \tau)$  defined in table (71). In this section we calculate the function  $K(s)$  defined by (30). It is easily checked that the operator  $M(s)$ , defined by the same integral formula (28), defines an intertwining map from  $I_\Phi(s, \chi, \chi_0, \tau)$  to  $I_\Phi(-s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ . In fact, there is a commutative diagram

$$\begin{array}{ccc} I_\Phi(s, \chi, \chi_0, \tau) & \xrightarrow{M(s)} & I_\Phi(-s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau) \\ \downarrow & & \downarrow \\ I_W(s, \chi, \chi_0, \tau) & \xrightarrow[M(s)]{} & I_W(-s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau) \end{array}$$

in which the vertical maps are the intertwining operators  $\Phi \mapsto W_\Phi$  given, in the region of convergence, by formula (68). The commutativity follows from a straightforward calculation in the region of convergence, and by analytic continuation outside this region. It follows that the function  $K(s)$ , instead of (30), can also be determined from the equation

$$M(s)\Phi^\#(\cdot, s, \chi, \chi_0, \tau) = K(s)\Phi^\#(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau). \quad (87)$$

Here,  $\Phi^\# \in I_\Phi(s, \chi, \chi_0, \tau)$  is defined in table (71). At this point, we do not yet know in all cases that a function  $K(s)$  with the property (87) actually exists. We *do* know that it exists in the Cases A and B defined in (70); since  $M(s)$  preserves right transformation properties, this follows from the uniqueness statement in Theorem 1.3.6 ii) and iii). In view of the normalization (63), we have the formula

$$K(s) = \int_{N(\mathbb{R})} \Phi^\#(w_1 n \eta_0, s, \chi, \chi_0, \tau) dn \quad (88)$$

in Cases A and B. In Case C, part iv) of Theorem 1.3.6 assures that the left side of (87) is a linear combination of  $\Phi_{m, l, l_2, l+1}^\#$  and  $\Phi_{m, l, l_2, l-1}^\#$ . It would be more precise to write these functions as

$$\Phi_{m, l, l_2, l \pm 1}^\#(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau) \quad \text{or} \quad \Phi_{m, l, l_2, l \pm 1}^\#(\cdot, -s, \beta_2^{-1} \times \beta_1^{-1})$$

since they are defined with respect to the data  $(-s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ , and  $\chi \tau$  is a subrepresentation of  $\beta_2^{-1} \times \beta_1^{-1}$ . The calculation will show that this linear combination is precisely a function  $K(s)$  times the distinguished vector  $\Phi^\#(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$  for the data  $(-s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ . This will establish the existence of  $K(s)$  with the property (87) in all cases.

Concerning the measure on  $N(\mathbb{R})$ , similar remarks as in the  $p$ -adic case apply. As a measure space,  $N(\mathbb{R}) \cong \mathbb{R} \times \mathbb{C} \times \mathbb{C}$ . The measure on  $\mathbb{R}$  is the usual Lebesgue measure, but the measure on  $\mathbb{C}$  is *twice* the usual Lebesgue measure; see Sect. 2.2 of [61].

**Remark:** The reason we are calculating  $K(s)$  from equation (87) and not from equation (30) is that the relevant archimedean integrals are much easier to handle in the induced model than in the Whittaker model. The price one has to pay for this procedure are the non-explicit constants  $\kappa_{l_1, p, q}$  defined in (69). They will not appear any further in this section, but later in Sect. 2.2 when

we calculate local zeta integrals; see Corollary 2.2.3. In our application to the functional equation in Sect. 2.4, the unknown constants  $\kappa_{l_1,p,q}$  will cancel out with the constants  $a_{l_1,p,q}$  defined in (66), via the identity given in Lemma 1.3.8.

**1.5.1 Theorem.** *Let  $(\tau, V_\tau)$  be a generic, irreducible, admissible representation of  $\mathrm{GL}_2(\mathbb{R})$  with central character  $\omega_\tau$ . We assume that  $\tau$  is isomorphic to a subrepresentation of  $\beta_1 \times \beta_2$  with characters  $\beta_1, \beta_2$  of  $\mathbb{R}^\times$ . Let the complex numbers  $p$  and  $q$  be as defined in (46). Let  $l$  be a fixed positive integer. Let  $l_2 = -l_1$  in Case A,  $l_2 = -l$  in Case B, and  $l_2 = 1 - l$  in Case C. Let  $\chi_0$  be the character of  $\mathbb{C}^\times$  such that  $\chi_0|_{\mathbb{R}^\times} = \omega_\tau$  and  $\chi_0(\zeta) = \zeta^{l_2}$  for  $\zeta \in \mathbb{C}^\times$ ,  $|\zeta| = 1$ . Let  $\chi$  be the character of  $\mathbb{C}^\times$  given by (45). Let  $W^\# \in I_W(s, \chi, \chi_0, \tau)$  be the distinguished function defined in table (71). Then the identity (30) holds with the function  $K(s)$  given as follows.*

i) In Case A,

$$K(s) = 4\pi^{5/2} i^{2l-l_1} \frac{\Gamma(3s - \frac{q}{2} + \frac{1}{2})\Gamma(3s - \frac{q}{2})}{(3s - \frac{q}{2} + \frac{l_1}{2} - \frac{1}{2})^2 \Gamma(3s - \frac{q}{2} + \frac{l_1}{2} + \frac{3}{2} - l)\Gamma(3s - \frac{q}{2} + l - \frac{l_1}{2} - \frac{1}{2})}. \quad (89)$$

ii) In Case B,

$$K(s) = 4\pi^{5/2} i^l \frac{\Gamma(3s - \frac{q}{2} + \frac{1}{2})\Gamma(3s - \frac{q}{2})}{(3s - \frac{q}{2} + \frac{p}{2})(3s - \frac{q}{2} - \frac{p}{2})\Gamma(3s - \frac{q}{2} - \frac{l}{2} + \frac{1}{2})\Gamma(3s - \frac{q}{2} + \frac{l}{2} + \frac{1}{2})}. \quad (90)$$

iii) In Case C,

$$\begin{aligned} K(s) &= -4\pi^{5/2} i^{l+1} \frac{(3s - \frac{q}{2} - \frac{l}{2})(3s - \frac{q}{2} - 1 - \frac{p}{2})}{(3s - \frac{q}{2} + 1 + \frac{p}{2})(3s - \frac{q}{2} + \frac{p}{2})(3s - \frac{q}{2} - \frac{p}{2})} \\ &\quad \times \frac{\Gamma(3s - \frac{q}{2} + \frac{1}{2})\Gamma(3s - \frac{q}{2})}{\Gamma(3s - \frac{q}{2} + 1 - \frac{l}{2})\Gamma(3s - \frac{q}{2} + 1 + \frac{l}{2})}. \end{aligned} \quad (91)$$

**Proof.** i) In Case A, by (71), we have  $\Phi^\# = \Phi_{m,l,l_2,l_1}^\#$ , where  $m = l_1 - l$  and  $l_1$  is the lowest weight of the representation  $\tau$ . The function  $\Phi_{m,l,l_2,l_1}^\#$  is given in Proposition 1.3.4. By (88), we have to calculate

$$K(s) = \int_{N(\mathbb{R})} \Phi_{m,l,-l_1,l_1}^\#(w_1 n \eta_0, s, \chi, \chi_0, \tau) dn. \quad (92)$$

We abbreviate

$$u = \sqrt{1+x^2}, \quad v = \sqrt{1+y\bar{y}}, \quad w = \sqrt{1+z\bar{z}},$$

and

$$\begin{aligned} r_1 &= \begin{bmatrix} w^{-1} & zw^{-1} \\ -\bar{z}w^{-1} & w^{-1} \\ & w^{-1} & zw^{-1} \\ & -\bar{z}w^{-1} & w^{-1} \end{bmatrix}, \quad r_2 = \begin{bmatrix} u^{-1} & & xu^{-1} \\ & 1 & \\ -xu^{-1} & & u^{-1} \\ & & 1 \end{bmatrix}, \\ r_3 &= \begin{bmatrix} v^{-1} & & & yv^{-1} \\ & v^{-1} & \bar{y}v^{-1} & \\ & -yv^{-1} & v^{-1} & \\ -\bar{y}v^{-1} & & & v^{-1} \end{bmatrix}. \end{aligned}$$

The elements  $r_1, r_2, r_3$  lie in  $K_\infty^{G_2}$ . Starting from (92), it is not difficult to show that

$$K(s) = \int_{\mathbb{C}} \int_{\mathbb{C}} \int_{\mathbb{R}} u(uvw)^{q-6s-2} (vw^{-1})^p \Phi_{m,l,-l_1,l_1}^\#(w_1 r_3 r_2 r_1 \eta_0) dx dy dz. \quad (93)$$

A calculation verifies that, with  $k = w_1 r_3 r_2 r_1 \eta_0$ ,

$$\det(J(k, i_2)) = -i \frac{1-ix}{u}, \quad \det(J({}^t k, i_2)) = i \frac{1+ix}{u},$$

and

$$\hat{b}(k) = (1-z\bar{z}) \left( \frac{v^2 - ix(1-y\bar{y})}{uv^2w^2} \right) + 2i \frac{(y\bar{z} + \bar{y}z)}{v^2w^2}.$$

Hence

$$\begin{aligned} \Phi_{m,l,-l_1,l_1}^\#(k) &= (-i)^m \hat{b}(k)^{l_1-l} \det(J({}^t k, i_2))^{l-l_1} \det(J(k, i_2))^{-l_1} \\ &= i^{2l-l_1} \left( (1-z\bar{z}) \left( \frac{v^2 - ix(1-y\bar{y})}{uv^2w^2} \right) + 2i \frac{(y\bar{z} + \bar{y}z)}{v^2w^2} \right)^{l_1-l} \left( \frac{1+ix}{u} \right)^l, \end{aligned}$$

so that

$$\begin{aligned} K(s) &= i^{2l-l_1} \int_{\mathbb{C}} \int_{\mathbb{C}} \int_{\mathbb{R}} u(uvw)^{q-6s-2} (vw^{-1})^p \\ &\quad \left( (1-z\bar{z}) \left( \frac{v^2 - ix(1-y\bar{y})}{uv^2w^2} \right) + 2i \frac{(y\bar{z} + \bar{y}z)}{v^2w^2} \right)^{l_1-l} \left( \frac{1+ix}{u} \right)^l dx dy dz. \end{aligned}$$

We now introduce polar coordinates for  $y$  and  $z$ . More precisely, put  $y = \sqrt{f}e^{i\theta_1}$ ,  $z = \sqrt{g}e^{i\theta_2}$ , and let  $\theta = \theta_1 - \theta_2$ . Also, put  $s_0 = 3s + \frac{1}{2} + \frac{l_1-l}{2} - \frac{q}{2}$ . With these substitutions, and using the fact that  $p = l_1 - 1$ , the intertwining integral becomes

$$\begin{aligned} K(s) &= i^{2l-l_1} 2\pi \int_0^{2\pi} \int_{\mathbb{R}} \int_0^\infty \int_0^\infty (1+x^2)^{-s_0} (1+f)^{-s_0-1+\frac{l}{2}} (1+g)^{-s_0+\frac{l}{2}-l_1} \left( \frac{1+ix}{u} \right)^l \\ &\quad \left( (1-g)(2-(1-f)(1+ix)) + 4iu\sqrt{fg} \cos\theta \right)^{l_1-l} df dg dx d\theta. \end{aligned}$$

Note here that the measure on  $\mathbb{C}$  is twice the usual Lebesgue measure. By Lemma 1.5.2 further below, we get the result.

ii) Next we evaluate the intertwining integral in the case where  $\tau$  contains the weight  $l$ . As in the previous case,  $K(s)$  is given by formula (88). The same calculation that led to (93) now shows that

$$K(s) = \int_{\mathbb{C}} \int_{\mathbb{C}} \int_{\mathbb{R}} u(uvw)^{q-6s-2} (vw^{-1})^p \Phi_{m,l,-l,l}^\#(w_1 r_3 r_2 r_1 \eta_0) dx dy dz. \quad (94)$$

This time  $\Phi_{m,l,-l,l}^\# = i^l \left( \frac{1+ix}{u} \right)^l$ , so that

$$K(s) = i^l \int_{\mathbb{C}} \int_{\mathbb{C}} \int_{\mathbb{R}} u(uvw)^{q-6s-2} (vw^{-1})^p \left( \frac{1+ix}{u} \right)^l dx dy dz.$$

This integral can be calculated as before by using polar coordinates. The result follows.

iii) This case is the most complicated one, since we do not yet know that a function  $K(s)$  with the property (87) exists. We do know, however, by part iv) of Theorem 1.3.6, that there exist functions  $K_1(s)$  and  $K_2(s)$  such that

$$\begin{aligned} M(s)\Phi^\#(\cdot, s, \chi, \chi_0, \tau) &= K_1(s)\Phi_{1,l,l_2,l+1}^\#(\cdot, -s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau) \\ &\quad + K_2(s)\Phi_{1,l,l_2,l-1}^\#(\cdot, -s, \bar{\chi}^{-1}, \chi\bar{\chi}\chi_0, \chi\tau). \end{aligned} \quad (95)$$

The calculation of  $K_1(s)$  and  $K_2(s)$  is in the same spirit as in Cases A and B, and we omit the details. Eventually it turns out that (87) holds with  $K(s)$  as in (91). ■

We would like to thank Paul-Olivier Dehaye for his help with the proof of the following lemma, which was used in the above calculations.

**1.5.2 Lemma.** *For non-negative integers  $l$  and  $t$ , and for all  $s \in \mathbb{C}$  with  $\operatorname{Re}(s)$  large enough,*

$$\begin{aligned} &\int_0^{2\pi} \int_{\mathbb{R}} \int_0^\infty \int_0^\infty (1+x^2)^{-s} (1+f)^{-s-1+\frac{l}{2}} (1+g)^{-s-\frac{l}{2}-t} \left(\frac{1+ix}{u}\right)^l \\ &\quad \left((1-g)(2-(1-f)(1+ix)) + 4iu\sqrt{fg} \cos\theta\right)^t df dg dx d\theta \\ &= \frac{2\pi^{3/2}\Gamma(s-\frac{t}{2})\Gamma(s-\frac{t}{2}-\frac{1}{2})}{(s+\frac{l}{2}-1)^2\Gamma(s-\frac{l}{2}+1)\Gamma(s+\frac{l}{2}-t-1)}. \end{aligned}$$

**Proof.** Let  $LHS$  denote the quantity on the left hand side of the asserted formula. We start off by completely expanding  $((1-g)(2-(1-f)(1+ix)) + 4iu\sqrt{fg} \cos\theta)^t$  using the binomial theorem. Then, using (6.16), (6.17) of [6] and the following well-known formulas,

$$\int_0^{2\pi} \cos(\theta)^k d\theta = \begin{cases} 0 & \text{if } k \text{ is odd,} \\ 2\sqrt{\pi} \frac{\Gamma(\frac{k+1}{2})}{\Gamma(\frac{k+2}{2})} & \text{if } k \text{ is even,} \end{cases}$$

$$\int_0^\infty r^{t_1} (1+r)^{-t_2} dr = \frac{\Gamma(1+t_1)\Gamma(-1+t_2-t_1)}{\Gamma(t_2)},$$

we arrive at (using the multinomial symbol)

$$LHS = \sum_{k,j,r,v} \left( (-1)^{k+r+v+j} 2^{2k+t-j+1} \binom{t}{2k, j, t-2k-j} \binom{t-2k}{v} \binom{j}{v} \frac{\Gamma(k+\frac{1}{2})\Gamma(1+k+r)}{\Gamma(k+1)\Gamma(s+\frac{l}{2}+t)} \pi \right. \\ \left. \frac{\Gamma(-1+s+t-k-r+\frac{l}{2})\Gamma(s-v-k-\frac{l}{2})\Gamma(1+k+v)\Gamma(s-k-\frac{j}{2})\Gamma(s-k-\frac{j}{2}-\frac{1}{2})}{\Gamma(s-\frac{l}{2}-k-j)\Gamma(s+\frac{l}{2}-k)\Gamma(s-\frac{l}{2}+1)} \right),$$

where the sum is taken over non-negative integers  $k, j, r, v$  satisfying  $2k+j \leq t, r+2k \leq t$  and  $v \leq j$ . Next, using well-known summation formulas for the gamma functions and algebraic manipulations (we omit the details of this step, which were performed with the aid of Mathematica), it turns out that the above expression simplifies significantly. As a result, the lemma reduces to

proving a certain algebraic identity. Let  $x^{(n)} = x(x+1)\dots(x+n-1)$  denote the Pochhammer symbol. Then the identity we are reduced to proving is

$$\sum_{k=0}^T \sum_{\substack{v \geq 0, n \geq 0 \\ v+n \leq 4T+1}} 4^k \frac{(-1)^{k+v}}{n!v!(2T-2k)!} \cdot \frac{(x+k-n)^{(n)}(x-k+1)^{(v)}}{(x-2T+v)^{(k+1)}(x+2T-k-n)^{(k+1)}} = -\frac{1}{x^2(2T)!},$$

where  $T$  is any non-negative integer, and  $x$  is an indeterminate. To prove this identity, observe that each summand above can be written using the partial fraction decomposition as a sum of rational functions, where each numerator is a rational number and the denominators are terms of the form  $(x-a)^b$  with  $b$  equal to 1 or 2, and  $-3T-1 \leq a \leq 3T+1$ . So to prove the identity, it is enough to show that the sum of the numerators coincide on both sides for each such denominator. This is straightforward combinatorics, and we omit the details. ■

## 2 Global $L$ -functions for $\mathrm{GSp}_4 \times \mathrm{GL}_2$

In this section, we will use the integral defined by Furusawa in [15] to obtain an integral representation of the  $L$ -function of a Siegel cusp form of full level of degree two twisted by any irreducible, cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$ . We will use this to obtain the functional equation of the  $L$ -function, with some restriction on the  $\mathrm{GL}_2$  representation. We will first do the non-archimedean calculation, followed by the archimedean calculation and put it all together to get the global result.

### 2.1 Bessel models for $\mathrm{GSp}_4$

Let  $F$  be an algebraic number field and  $\mathbb{A}_F$  its ring of adeles. We fix three elements  $\mathbf{a}, \mathbf{b}, \mathbf{c} \in F$  such that  $\mathbf{d} = \mathbf{b}^2 - 4\mathbf{a}\mathbf{c}$  is a non-square in  $F^\times$ . Then  $L = F(\sqrt{\mathbf{d}})$  is a quadratic field extension of  $F$ . Let

$$S = \begin{bmatrix} \mathbf{a} & \frac{\mathbf{b}}{2} \\ \frac{\mathbf{b}}{2} & \mathbf{c} \end{bmatrix}, \quad \xi = \begin{bmatrix} \frac{\mathbf{b}}{2} & \mathbf{c} \\ -\mathbf{a} & \frac{-\mathbf{b}}{2} \end{bmatrix}.$$

Then  $F(\xi) = F + F\xi$  is a two-dimensional  $F$ -algebra isomorphic to  $L$ , an isomorphism being given by  $x + y\xi \mapsto x + y\frac{\sqrt{\mathbf{d}}}{2}$ . The determinant map on  $F(\xi)$  corresponds to the norm map on  $L$ . Let

$$T = \{g \in \mathrm{GL}_2 \mid {}^t g S g = \det(g)S\}. \tag{96}$$

This is an algebraic  $F$ -group with  $T(F) = F(\xi)^\times \cong L^\times$  and  $T(\mathbb{A}_F) \cong \mathbb{A}_L^\times$ . We consider  $T$  a subgroup of  $H = \mathrm{GSp}_4$  via

$$T \ni g \longmapsto \begin{bmatrix} g & \\ & \det(g) {}^t g^{-1} \end{bmatrix} \in H.$$

Let

$$U = \left\{ \begin{bmatrix} 1_2 & X \\ & 1_2 \end{bmatrix} \in H \mid {}^t X = X \right\}$$

and  $R = TU$ . We call  $R$  the *Bessel subgroup* of  $H$  (with respect to the given data  $\mathbf{a}, \mathbf{b}, \mathbf{c}$ ). Let  $\psi$  be a non-trivial character  $F \backslash \mathbb{A}_F \rightarrow \mathbb{C}^\times$ , chosen once and for all. Let  $\theta : U(\mathbb{A}_F) \rightarrow \mathbb{C}^\times$  be the character given by

$$\theta\left(\begin{bmatrix} 1 & X \\ & 1 \end{bmatrix}\right) = \psi(\mathrm{tr}(SX)). \tag{97}$$

We have  $\theta(t^{-1}ut) = \theta(u)$  for all  $u \in U(\mathbb{A}_F)$  and  $t \in T(\mathbb{A}_F)$ . Hence, if  $\Lambda$  is any character of  $T(\mathbb{A}_F) \cong \mathbb{A}_L^\times$ , then the map  $tu \mapsto \Lambda(t)\theta(u)$  defines a character of  $R(\mathbb{A}_F)$ . We denote this character by  $\Lambda \otimes \theta$ .

Analogous definitions can be made over any local field  $F$ . In this case, let  $\pi$  be an irreducible, admissible representation of  $H(F)$ . Let  $\Lambda$  be a character of  $T(F) \cong L^\times$  such that the restriction of  $\Lambda$  to  $F^\times$  coincides with the central character of  $\pi$ . Let  $\Lambda \otimes \theta$  be the character of  $R(F)$  defined above. We say that  $\pi$  has a *Bessel model* of type  $(S, \Lambda, \psi)$  if  $\pi$  is isomorphic to a space of functions  $B : H(F) \rightarrow \mathbb{C}$  with the transformation property

$$B(tuh) = \Lambda(t)\theta(u)B(h) \quad \text{for all } t \in T(F), u \in U(F), h \in H(F),$$

with the action of  $H(F)$  on this space given by right translation. Such a model, if it exists, is known to be unique; we denote it by  $\mathcal{B}_{S,\Lambda,\psi}(\pi)$ .

Now let  $F$  be global, and let  $\pi = \otimes \pi_v$  be a cuspidal, automorphic representation of  $H(\mathbb{A}_F)$ . Let  $V_\pi$  be the space of automorphic forms realizing  $\pi$ . Assume that a Hecke character  $\Lambda$  as above is chosen such that the restriction of  $\Lambda$  to  $\mathbb{A}_F^\times$  coincides with  $\omega_\pi$ , the central character of  $\pi$ . For each  $\phi \in V_\pi$  consider the corresponding Bessel function

$$B_\phi(g) = \int_{Z_H(\mathbb{A}_F)R(F) \backslash R(\mathbb{A}_F)} (\Lambda \otimes \theta)(r)^{-1} \phi(rg) dr, \quad (98)$$

where  $Z_H$  is the center of  $H$ . If one of these integrals is non-zero, then all are non-zero, and we obtain a model  $\mathcal{B}_{S,\Lambda,\psi}(\pi)$  of  $\pi$  consisting of functions on  $H(\mathbb{A}_F)$  with the obvious transformation property on the left with respect to  $R(\mathbb{A}_F)$ . In this case, we say that  $\pi$  has a *global Bessel model* of type  $(S, \Lambda, \psi)$ . It implies that the *local* Bessel model  $\mathcal{B}_{S,\Lambda_v,\psi_v}(\pi_v)$  exists for every place  $v$  of  $F$ . In fact, there is a canonical isomorphism

$$\bigotimes_v \mathcal{B}_{S,\Lambda_v,\psi_v}(\pi_v) \cong \mathcal{B}_{S,\Lambda,\psi}(\pi).$$

If  $(B_v)_v$  is a collection of local Bessel functions  $B_v \in \mathcal{B}_{S,\Lambda_v,\psi_v}(\pi_v)$  such that  $B_v|_{H(\mathfrak{o}_v)} = 1$  for almost all  $v$ , then this isomorphism is such that  $\otimes_v B_v$  corresponds to the global function

$$B(g) = \prod_v B_v(g_v), \quad g = (g_v)_v \in H(\mathbb{A}_F). \quad (99)$$

### Explicit formulas: the spherical Bessel function

Explicit formulas for local Bessel functions are only known in a few cases. One of these is the  $p$ -adic unramified case, which we review next. Hence, let  $F$  be a non-archimedean local field of characteristic zero. Let the character  $\psi$  of  $F$  have conductor  $\mathfrak{o}$ , the ring of integers. Let  $(\pi, V_\pi)$  be an unramified, irreducible, admissible representation of  $H(F)$ . Let  $\Lambda$  be an unramified character of  $T(F) \cong L^\times$ . We assume that  $V_\pi = \mathcal{B}_{S,\Lambda,\psi}(\pi)$  is the Bessel model with respect to the character  $\Lambda \otimes \theta$  of  $R(F)$ . Let  $B \in V_\pi$  be a spherical vector. By [58], Proposition 2-5, we have  $B(1) \neq 0$ . For  $l, m \in \mathbb{Z}$  let

$$h(l, m) = \begin{bmatrix} \varpi^{2m+l} & & & \\ & \varpi^{m+l} & & \\ & & 1 & \\ & & & \varpi^m \end{bmatrix}. \quad (100)$$

Then, as in (3.4.2) of [15],

$$H(F) = \bigsqcup_{l \in \mathbb{Z}} \bigsqcup_{m \geq 0} R(F)h(l, m)K^H, \quad K^H = H(\mathfrak{o}). \quad (101)$$

By Lemma (3.4.4) of [15] we have  $B(h(l, m)) = 0$  for  $l < 0$ , so that  $B$  is determined by the values  $B(h(l, m))$  for  $l, m \geq 0$ . In [58], 2-4, Sugano has given a formula for  $B(h(l, m))$  in terms of a generating function. The full formula is required only in the case where the  $\mathrm{GL}_2$  representation  $\tau$  is unramified; this case has been treated in [15]. For other cases we only require the values  $B(h(l, 0))$ , which are given by

$$\sum_{l \geq 0} B(h(l, 0))y^l = \frac{H(y)}{Q(y)}, \quad (102)$$

where

$$Q(y) = \prod_{i=1}^4 (1 - \gamma^{(i)}(\varpi)q^{-3/2}y) \quad (103)$$

and

$$H(y) = \begin{cases} 1 - q^{-4}\Lambda(\varpi)y^2 & \text{if } (\frac{L}{\mathfrak{p}}) = -1, \\ 1 - q^{-2}\Lambda(\varpi_L)y & \text{if } (\frac{L}{\mathfrak{p}}) = 0, \\ 1 - q^{-2}(\Lambda(\varpi_L) + \Lambda(\varpi\varpi_L^{-1}))y + q^{-4}\Lambda(\varpi)y^2 & \text{if } (\frac{L}{\mathfrak{p}}) = 1. \end{cases} \quad (104)$$

The  $\gamma^{(i)}$  are the Satake parameters of  $\pi$ , as in Sect. (3.6) of [15].

### Explicit formulas: the highest weight case

Another situation where an explicit formula for a Bessel function is known is the archimedean lowest weight case. Hence, let  $F = \mathbb{R}$ . Let  $l$  be an integer such that  $l \geq 2$ . Let  $\pi$  be the discrete series representation (or limit of such if  $l = 2$ ) of  $\mathrm{PGSp}_4(\mathbb{R})$  with minimal  $K$ -type  $(l, l)$ ; here, we write elements of the weight lattice as pairs of integers, precisely as in [44], Sect. 2.1. Such representations  $\pi$  appear as the archimedean components of the automorphic representations of  $H(\mathbb{A})$  attached to (scalar valued) Siegel modular forms of weight  $l$ . Recall that  $S$  is a positive definite matrix. Let the function  $B : H(\mathbb{R}) \rightarrow \mathbb{C}$  be defined by

$$B(h) := \begin{cases} \mu_2(h)^l \overline{\det(J(h, i_2))^{-l}} e^{-2\pi i \operatorname{tr}(Sh\langle i_2 \rangle)} & \text{if } h \in H^+(\mathbb{R}), \\ 0 & \text{if } h \notin H^+(\mathbb{R}), \end{cases} \quad (105)$$

where  $i_2 = \begin{bmatrix} i & \\ & i \end{bmatrix}$ . One can check that  $B$  satisfies the Bessel transformation property with the character  $\Lambda \otimes \theta$  of  $R(\mathbb{R})$ , where  $\Lambda$  is trivial. Also

$$B(hk) = \det(J(k, i_2))^l B(h) \quad \text{for } h \in H(\mathbb{R}), k \in K_\infty^H. \quad (106)$$

In fact, by the considerations in [58] 1-3, or by [44] Theorem 3.4,  $B$  is the highest weight vector (weight  $(-l, -l)$ ) in  $\mathcal{B}_{S, \Lambda, \psi}(\pi)$ . Note that the function  $B$  is determined by its values on a set of representatives for  $R(\mathbb{R}) \backslash H(\mathbb{R}) / K_\infty^H$ . Such a set can be obtained as follows. Let  $T^1(\mathbb{R}) = T(\mathbb{R}) \cap \mathrm{SL}(2, \mathbb{R})$ . Then  $T(\mathbb{R}) = T^1(\mathbb{R}) \cdot \left\{ \begin{bmatrix} \zeta & \\ & \zeta \end{bmatrix} : \zeta > 0 \right\}$ . As in [15], p. 211, let  $t_0 \in \mathrm{GL}_2(\mathbb{R})^+$  be

such that  $T^1(\mathbb{R}) = t_0 \mathrm{SO}(2) t_0^{-1}$ . (We will make a specific choice of  $t_0$  when we choose the matrix  $S$  below.) It is not hard to see that

$$H(\mathbb{R}) = R(\mathbb{R}) \cdot \left\{ \begin{bmatrix} \lambda t_0 & [\zeta & \zeta^{-1}] \\ & t_0^{-1} & [\zeta^{-1} & \zeta] \end{bmatrix} : \lambda \in \mathbb{R}^\times, \zeta \geq 1 \right\} \cdot K_\infty^H. \quad (107)$$

One can check that the double cosets in (107) are pairwise disjoint.

## 2.2 Local zeta integrals

Let  $F$  be a non-archimedean local field of characteristic zero, or  $F = \mathbb{R}$ . Let  $\mathbf{a}, \mathbf{b}, \mathbf{c} \in F$  and  $L, \alpha, \eta$  be according to our conventions; see (3), (4), (5). Let  $\tau, \chi_0, \chi$  be as in Corollary 1.2.4 (non-archimedean case) resp. Corollary 1.3.6 (archimedean case). Let  $W^\#(\cdot, s)$  be the unique vector in  $I(s, \chi, \chi_0, \tau)$  exhibited in these corollaries. The calculation in the proof of Theorem (2.4) of [15] shows that

$$W^\#(\eta t u h, s) = \Lambda(t)^{-1} \theta(u)^{-1} W^\#(\eta h, s) \quad \text{for all } t \in T(F), u \in U(F), h \in H(F). \quad (108)$$

Here,  $\Lambda$  is an unramified character of  $L^\times$  in the non-archimedean case, and  $\Lambda = 1$  in the archimedean case; we always have  $\chi(\zeta) = \Lambda(\bar{\zeta})^{-1} \chi_0(\bar{\zeta})^{-1}$ . Let  $\pi$  be an irreducible, admissible representation of  $H(F)$  which has a Bessel model of type  $(S, \Lambda, \psi)$ . Then, for any  $B \in \mathcal{B}_{S, \Lambda, \psi}(\pi)$ , equation (108) shows that the integral

$$Z(s, W^\#, B) = \int_{R(F) \backslash H(F)} W^\#(\eta h, s) B(h) dh \quad (109)$$

makes sense. We shall now explicitly calculate these integrals in the case of  $B$  being the spherical vector in an unramified  $p$ -adic representation  $\pi$ , and  $B$  being the highest weight vector in an archimedean (limit of) discrete series representation with scalar minimal  $K$ -type.

### The non-archimedean case

Assume that  $F$  is non-archimedean. Recall the explicit formula for the distinguished function  $W^\#(\cdot, s)$  given in Corollary 1.2.4. It involves  $W^{(0)}$ , the normalized local newform in the Whittaker model of  $\tau$  with respect to the character  $\psi^{-\mathbf{c}}(x) = \psi(-\mathbf{c}x)$ . Since this character has conductor  $\mathfrak{o}$ , the values  $W^{(0)}\left(\begin{bmatrix} \varpi^l & \\ & 1 \end{bmatrix}\right)$  are zero for negative  $l$ . For non-negative  $l$ , one can use formulas for

the local newform with respect to the congruence subgroup  $\mathrm{GL}_2(\mathfrak{o}) \cap \left[ \begin{array}{cc} \mathfrak{o} & \mathfrak{o} \\ \mathfrak{p}^n & 1 + \mathfrak{p}^n \end{array} \right]$  (given, amongst

other places, in [53]), together with the local functional equation, to obtain the following.

$$\begin{array}{ll}
\tau & W^{(0)}\left(\begin{bmatrix} \varpi^l \\ 1 \end{bmatrix}\right) \quad (l \geq 0) \\
\hline
\beta_1 \times \beta_2 \text{ with } \beta_1, \beta_2 \text{ unramified, } \beta_1 \beta_2^{-1} \neq ||^{\pm 1} & q^{-l/2} \sum_{k=0}^l \beta_1(\varpi)^k \beta_2(\varpi)^{l-k} \\
\beta_1 \times \beta_2 \text{ with } \beta_1 \text{ unramified, } \beta_2 \text{ ramified} & \beta_2(\varpi^l) q^{-\frac{l}{2}} \\
\Omega \text{ St}_{\text{GL}_2} \text{ with } \Omega \text{ unramified} & \Omega(\varpi^l) q^{-l} \\
\text{supercuspidal OR ramified twist of Steinberg} & 1 \quad \text{if } l = 0 \\
\text{OR } \beta_1 \times \beta_2 \text{ with } \beta_1, \beta_2 \text{ ramified, } \beta_1 \beta_2^{-1} \neq ||^{\pm 1} & 0 \quad \text{if } l > 0
\end{array} \tag{110}$$

Assume that  $\pi$  is an unramified representation and that  $B \in \mathcal{B}_{S,\Lambda,\psi}(\pi)$  is the spherical Bessel function as in (102). In the following we shall assume that the conductor  $\mathfrak{p}^n$  of  $\tau$  satisfies  $n > 0$ , since for unramified  $\tau$  the local integral has been computed by Furusawa; see Theorem (3.7) in [15]. Since both functions  $B$  and  $W^\#$  are right  $K^H$ -invariant, it follows from (101) that the integral (109) is given by

$$Z(s, W^\#, B) = \sum_{l,m \geq 0} B(h(l,m)) W^\#(\eta h(l,m), s) V_m q^{3m+3l}. \tag{111}$$

Here, as in Sect. 3.5 of [15],  $V_m = \text{vol}(T(F) \backslash T(F) \begin{bmatrix} \varpi^m & \\ & 1 \end{bmatrix} \text{GL}_2(\mathfrak{o}))$ . Calculations confirm that  $\eta h(l,m)$  lies in the support of  $W^\#(\cdot, s)$  if and only if  $m = 0$ . It follows that the sum (111) reduces to

$$Z(s, W^\#, B) = \sum_{l \geq 0} B(h(l,0)) W^\#(\eta h(l,0), s) q^{3l}. \tag{112}$$

By (42),

$$W^\#(\eta h(l,0), s) = q^{-3(s+1/2)l} \omega_\pi(\varpi^{-l}) \omega_\tau(\varpi^{-l}) W^{(0)}\left(\begin{bmatrix} \varpi^l \\ 1 \end{bmatrix}\right). \tag{113}$$

Substituting the values of  $W^{(0)}\left(\begin{bmatrix} \varpi^l \\ 1 \end{bmatrix}\right)$  from the table above and the values of  $B(h(l,0))$  from (102), we get the following result.

**2.2.1 Theorem.** *Let  $\tau, \chi, \chi_0, \Lambda$  and  $W^\#(\cdot, s)$  be as in Corollary 1.2.4. Let  $\pi$  be an irreducible, admissible, unramified representation of  $H(F)$ , and let  $B$  be the unramified Bessel function given by formula (102). Then the local zeta integral  $Z(s, W^\#, B)$  defined in (109) is given by*

$$Z(s, W^\#, B) = \frac{L(3s + \frac{1}{2}, \tilde{\tau} \times \tilde{\tau})}{L(6s + 1, \chi|_{F^\times}) L(3s + 1, \tau \times \mathcal{A}\mathcal{I}(\Lambda) \times \chi|_{F^\times})} Y(s), \tag{114}$$

where

$$Y(s) = \begin{cases} 1 & \text{if } \tau = \beta_1 \times \beta_2, \beta_1, \beta_2 \text{ unramified,} \\ L(6s + 1, \chi|_{F^\times}) & \text{if } \tau = \beta_1 \times \beta_2, \beta_1 \text{ unram., } \beta_2 \text{ ram., } (\frac{L}{\mathfrak{p}}) = \pm 1, \\ & \text{OR } \tau = \beta_1 \times \beta_2, \beta_1 \text{ unram., } \beta_2 \text{ ram., } \\ & (\frac{L}{\mathfrak{p}}) = 0 \text{ and } \beta_2 \chi_{L/F} \text{ ramified,} \\ & \text{OR } \tau = \Omega \text{St}_{\text{GL}(2)}, \Omega \text{ unramified,} \\ \frac{L(6s + 1, \chi|_{F^\times})}{1 - \Lambda(\varpi_L)(\omega_\pi \beta_2)^{-1}(\varpi)q^{-3s-1}} & \text{if } \tau = \beta_1 \times \beta_2, \beta_1 \text{ unram., } \beta_2 \text{ ram., } (\frac{L}{\mathfrak{p}}) = 0, \\ & \text{and } \beta_2 \chi_{L/F} \text{ unramified,} \\ L(6s + 1, \chi|_{F^\times})L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times}) & \text{if } \tau = \beta_1 \times \beta_2, \beta_1, \beta_2 \text{ ramified,} \\ & \text{OR } \tau = \Omega \text{St}_{\text{GL}(2)}, \Omega \text{ ramified,} \\ & \text{OR } \tau \text{ supercuspidal.} \end{cases}$$

**[check!]** In (114),  $\tilde{\pi}$  and  $\tilde{\tau}$  denote the contragredient of  $\pi$  and  $\tau$ , respectively. The symbol  $\mathcal{AI}(\Lambda)$  stands for the  $\text{GL}_2(F)$  representation attached to the character  $\Lambda$  of  $L^\times$  via automorphic induction, and  $\chi_{L/F}$  stands for the quadratic character of  $F^\times$  associated with the extension  $L/F$ . The function  $L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})$  is a standard  $L$ -factor for  $\text{GL}_2 \times \text{GL}_2 \times \text{GL}_1$ .

**Proof.** If  $\tau = \beta_1 \times \beta_2$  with unramified  $\beta_1$  and  $\beta_2$ , then this is Theorem (3.7) in Furusawa's paper [15]. If  $\tau = \beta_1 \times \beta_2$  with unramified  $\beta_1$  and ramified  $\beta_2$ , then, from the local Langlands correspondence, we have the following  $L$ -functions attached to the representations  $\tilde{\pi} \times \tilde{\tau}$  of  $\text{GSp}_4(F) \times \text{GL}_2(F)$  and  $\tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times}$  of  $\text{GL}_2(F) \times \text{GL}_2(F) \times \text{GL}_1(F)$ ,

$$L(s, \tilde{\pi} \times \tilde{\tau}) = \prod_{i=1}^4 (1 - (\gamma^{(i)} \beta_1)^{-1}(\varpi)q^{-s})^{-1}, \quad (115)$$

where  $\gamma^{(i)}$  are the Satake parameters of  $\pi$ , as in Sect. (3.6) of [15], and

$$\frac{1}{L(s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})} = \begin{cases} 1 - (\Lambda(\omega_\pi \beta_1)^{-2})(\varpi)q^{-2s} & \text{if } (\frac{L}{\mathfrak{p}}) = -1, \\ 1 - \Lambda(\varpi_L)(\omega_\pi \beta_1)^{-1}(\varpi)q^{-s} & \text{if } (\frac{L}{\mathfrak{p}}) = 0 \text{ and } \beta_2 \chi_{L/F} \text{ ram.,} \\ (1 - \Lambda(\varpi_L)(\omega_\pi \beta_1)^{-1}(\varpi)q^{-s}) & \\ (1 - \Lambda(\varpi_L)(\omega_\pi \beta_2)^{-1}(\varpi)q^{-s}) & \text{if } (\frac{L}{\mathfrak{p}}) = 0 \text{ and } \beta_2 \chi_{L/F} \text{ unram.,} \\ (1 - \Lambda(\varpi_L)(\omega_\pi \beta_1)^{-1}(\varpi)q^{-s}) & \\ (1 - \Lambda(\varpi \varpi_L^{-1})(\omega_\pi \beta_1)^{-1}(\varpi)q^{-s}) & \text{if } (\frac{L}{\mathfrak{p}}) = 1. \end{cases}$$

The desired result therefore follows from (103) and (104). If  $\tau$  is an unramified twist of the Steinberg representation, then the result was proved in Theorem 3.8.1 of [45]. In all remaining cases we have  $L(s, \tilde{\pi} \times \tilde{\tau}) = 1$  and  $Z(s, W^\#, B) = 1$ , so that the asserted formula holds. ■

### The archimedean case

Now let  $F = \mathbb{R}$ . We will calculate the zeta integral (109) for the distinguished function  $W^\#$  given in Theorem 1.3.6. It is enough to calculate these integrals for the functions  $W_{m,l,l_2,l_1}^\#$ , where  $l_1$  is one of the weights occurring in  $\tau$ , and where  $l_2 \in \mathbb{Z}$  has the same parity as  $l_1$ . Recall the explicit formula (67) for these functions.

As for the Bessel function ingredient in (109), let  $\pi$  be a (limit of) discrete series representation of  $\mathrm{PGSp}_4(\mathbb{R})$  with scalar minimal  $K$ -type  $(l, l)$ , where  $l \geq 2$ . Let  $B : H(\mathbb{R}) \rightarrow \mathbb{C}$  be the function defined in (105). Then  $B$  is a vector of weight  $(-l, -l)$  in  $\mathcal{B}_{S, \Lambda, \psi}(\pi)$ , where  $\Lambda = 1$  and  $\psi(x) = e^{-2\pi i x}$ . By (74) and (106), the function  $W^\#(\eta h, s)B(h)$  is right invariant under  $K_\infty^H$ . Using this fact and the disjoint double coset decomposition (107), we obtain

$$\begin{aligned} Z(s, W_{m,l,l_2,l_1}^\#, B) &= \pi \int_{\mathbb{R}^\times} \int_1^\infty W_{m,l,l_2,l_1}^\# \left( \eta \begin{bmatrix} \lambda t_0 & [\zeta & \zeta^{-1}] \\ & {}^t t_0^{-1} & [\zeta^{-1} & \zeta] \end{bmatrix}, s \right) \\ &\quad B \left( \begin{bmatrix} \lambda t_0 & [\zeta & \zeta^{-1}] \\ & {}^t t_0^{-1} & [\zeta^{-1} & \zeta] \end{bmatrix} \right) (\zeta - \zeta^{-3}) \lambda^{-4} d\zeta d\lambda; \end{aligned} \quad (116)$$

see (4.6) of [15] for the relevant integration formulas. The above calculations are valid for any choice of  $\mathbf{a}, \mathbf{b}, \mathbf{c}$  as long as  $S = \begin{bmatrix} \mathbf{a} & \mathbf{b}/2 \\ \mathbf{b}/2 & \mathbf{c} \end{bmatrix}$  is positive definite. We will compute (116), in two special cases, namely when  $S$  is of the form  $S = \begin{bmatrix} D/4 & \\ & 1 \end{bmatrix}$  or  $S = \begin{bmatrix} (1+D)/4 & 1/2 \\ 1/2 & 1 \end{bmatrix}$  with a positive number  $D$ . By the argument in Sect. 4.4 of [45], we may assume that  $S$  is of the first kind. Then

$$\eta = \begin{bmatrix} 1 & & & \\ \frac{\sqrt{-D}}{2} & 1 & & \\ & 1 & \frac{\sqrt{-D}}{2} & \\ & & & 1 \end{bmatrix}, \text{ and we can choose } t_0 = \begin{bmatrix} 2^{1/2} D^{-1/4} & \\ & 2^{-1/2} D^{1/4} \end{bmatrix}. \text{ From formula (105),}$$

$$B \left( \begin{bmatrix} \lambda t_0 & [\zeta & \zeta^{-1}] \\ & {}^t t_0^{-1} & [\zeta^{-1} & \zeta] \end{bmatrix} \right) = \begin{cases} \lambda^l e^{-2\pi\lambda D^{1/2} \frac{\zeta^2 + \zeta^{-2}}{2}} & \text{if } \lambda > 0, \\ 0 & \text{if } \lambda < 0. \end{cases} \quad (117)$$

Next, the argument of  $W_{m,l,l_2,l_1}^\#$  can be rewritten as an element of  $MN K_\infty^{G_2}$  as

$$\begin{bmatrix} \lambda D^{-\frac{1}{4}} \left( \frac{\zeta^2 + \zeta^{-2}}{2} \right)^{-\frac{1}{2}} & & & \\ & \lambda D^{\frac{1}{4}} \left( \frac{\zeta^2 + \zeta^{-2}}{2} \right)^{\frac{1}{2}} & & \\ & & D^{\frac{1}{4}} \left( \frac{\zeta^2 + \zeta^{-2}}{2} \right)^{\frac{1}{2}} & \\ & & & D^{-\frac{1}{4}} \left( \frac{\zeta^2 + \zeta^{-2}}{2} \right)^{-\frac{1}{2}} \end{bmatrix} \begin{bmatrix} 1 & -i\zeta^2 \\ 0 & 1 \\ & & 1 & 0 \\ & & -i\zeta^2 & 1 \end{bmatrix} k,$$

where  $k = \begin{bmatrix} k_0 & \\ & k_0 \end{bmatrix}$  with  $k_0 = (\zeta^2 + \zeta^{-2})^{-1/2} \begin{bmatrix} \zeta^{-1} & i\zeta \\ i\zeta & \zeta^{-1} \end{bmatrix} \in \mathrm{SU}(2)$ . From now on assume that  $m = |l - l_1|$ . We have

$$\Phi_{m,l,l_2,l_1}^\# \left( \begin{bmatrix} k_0 & \\ & k_0 \end{bmatrix} \right) = \left( \frac{\zeta^2 + \zeta^{-2}}{2} \right)^{-m},$$

and hence

$$\begin{aligned} W_{m,l,l_2,l_1}^{\#}\left(\eta \begin{bmatrix} \lambda t_0 \begin{bmatrix} \zeta & \\ & \zeta^{-1} \end{bmatrix} & \\ & t_0^{-1} \begin{bmatrix} \zeta^{-1} & \\ & \zeta \end{bmatrix} \end{bmatrix}, s\right) \\ = \left(\frac{\zeta^2 + \zeta^{-2}}{2}\right)^{-|l-l_1|} \left|\lambda D^{-\frac{1}{2}} \left(\frac{\zeta^2 + \zeta^{-2}}{2}\right)^{-1}\right|^{3(s+\frac{1}{2})} \omega_{\tau}(\lambda)^{-1} W_{l_1}\left(\begin{bmatrix} \lambda D^{\frac{1}{2}} \left(\frac{\zeta^2 + \zeta^{-2}}{2}\right) & \\ & 1 \end{bmatrix}\right). \end{aligned} \quad (118)$$

If  $q \in \mathbb{C}$  is as in (46), then  $\omega_{\tau}(y) = y^q$  for  $y > 0$ . It follows from (65), (117) and (118) that

$$\begin{aligned} Z(s, W_{m,l,l_2,l_1}^{\#}, B) = a^+ \pi D^{-\frac{3s}{2} - \frac{3}{4} + \frac{q}{4}} (4\pi)^{\frac{q}{2}} \int_0^\infty \int_1^\infty \lambda^{3s+\frac{3}{2}+l-\frac{q}{2}} \left(\frac{\zeta^2 + \zeta^{-2}}{2}\right)^{-3s-\frac{3}{2}+\frac{q}{2}-|l-l_1|} \\ W_{\frac{l_1}{2}, \frac{p}{2}}\left(4\pi\lambda D^{1/2} \frac{\zeta^2 + \zeta^{-2}}{2}\right) e^{-2\pi\lambda D^{1/2} \frac{\zeta^2 + \zeta^{-2}}{2}} (\zeta - \zeta^{-3}) \lambda^{-4} d\zeta d\lambda. \end{aligned} \quad (119)$$

The substitutions  $u = (\zeta^2 + \zeta^{-2})/2$  and  $x = 4\pi\lambda D^{1/2}u$ , together with the integral formula for the Whittaker function from [39, p. 316], we get

$$Z(s, W_{m,l,l_2,l_1}^{\#}, B) = a^+ \pi \frac{D^{-3s-\frac{l}{2}+\frac{q}{2}} (4\pi)^{-3s+\frac{3}{2}-l+q}}{6s+l+|l-l_1|-q-1} \frac{\Gamma(3s+l-1+\frac{p}{2}-\frac{q}{2})\Gamma(3s+l-1-\frac{p}{2}-\frac{q}{2})}{\Gamma(3s+l-\frac{l_1}{2}-\frac{1}{2}-\frac{q}{2})}.$$

Here, for the calculation of the  $u$ -integral, we have assumed that  $\operatorname{Re}(6s+l+|l-l_1|-q-1) > 0$ . We summarize our result in the following theorem. We will use the notation

$$\Gamma_{\mathbb{R}}(s) = \pi^{-s/2} \Gamma\left(\frac{s}{2}\right), \quad \Gamma_{\mathbb{C}}(s) = 2(2\pi)^{-s} \Gamma(s). \quad (120)$$

The proof of (123) below follows from the tables at the end of this section.

**2.2.2 Theorem.** Assume that the matrix  $S$  is of the form

$$S = \begin{bmatrix} D/4 & \\ & 1 \end{bmatrix} \quad \text{or} \quad S = \begin{bmatrix} (1+D)/4 & 1/2 \\ 1/2 & 1 \end{bmatrix} \quad (121)$$

with a positive number  $D$ . Let  $l \geq 2$  be an integer, and let  $\pi$  be the (limit of) discrete series representation of  $\operatorname{PGSp}_4(\mathbb{R})$  with scalar minimal  $K$ -type  $(l, l)$ . Let  $l_2 \in \mathbb{Z}$  and  $\tau, \chi_0, \chi$  be as in Corollary 1.3.7. Let  $l_1$  be one of the weights occurring in  $\tau$ , and let  $W_{|l-l_1|, l, l_2, l_1}^{\#}$  be the function defined in (67). Let  $B : H(\mathbb{R}) \rightarrow \mathbb{C}$  be the function defined in (105). Then, for  $\operatorname{Re}(6s+l+|l-l_1|-q-1) > 0$ , with the local archimedean integral as in (109),

$$\begin{aligned} Z(s, W_{|l-l_1|, l, l_2, l_1}^{\#}, B) = a_{l_1, p, q}^+ D^{-3s-\frac{l}{2}+\frac{q}{2}} 2^{-3s+\frac{1}{2}-l+\frac{3q}{2}+\frac{l_1}{2}} \pi^{1+\frac{q}{2}+\frac{l_1}{2}} \\ \times \frac{1}{6s+l+|l-l_1|-q-1} \frac{\Gamma_{\mathbb{C}}(3s+l-1+\frac{p}{2}-\frac{q}{2})\Gamma_{\mathbb{C}}(3s+l-1-\frac{p}{2}-\frac{q}{2})}{\Gamma_{\mathbb{C}}(3s+l-\frac{l_1}{2}-\frac{1}{2}-\frac{q}{2})}. \end{aligned} \quad (122)$$

Here,  $a_{l_1, p, q}^+$  is as defined in (66). The numbers  $p, q \in \mathbb{C}$  are defined in (46). With  $\Lambda$  being the trivial character, we can rewrite formula (122) as

$$Z(s, W_{|l-l_1|, l, l_2, l_1}^{\#}, B) = \frac{L(3s+\frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s+1, \chi|_{\mathbb{R}^{\times}}) L(3s+1, \tau \times \mathcal{A}\mathcal{I}(\Lambda) \times \chi|_{\mathbb{R}^{\times}})} Y_{l, l_1, p, q}(s), \quad (123)$$

where, with  $u = 0$  if  $l_1$  is even and  $u = 1/2$  if  $l_1$  is odd,

$$Y_{l,l_1,p,q}(s) = \begin{cases} \frac{a_{l_1,p,q}^+ D^{-3s-\frac{l}{2}+\frac{q}{2}} 2^{q-l+\frac{l_1}{2}+u} \pi^{1+\frac{q}{2}+\frac{l_1}{2}} (3s - \frac{q}{2} + \frac{p}{2})}{3s + \frac{l+|l-l_1|}{2} - \frac{1}{2} - \frac{q}{2}} \\ \times \frac{\Gamma_{\mathbb{C}}(3s + l - 1 - \frac{p}{2} - \frac{q}{2}) \Gamma_{\mathbb{C}}(3s + \frac{1}{2} - \frac{q}{2} + u)}{\Gamma_{\mathbb{C}}(3s + \frac{1}{2} - \frac{q}{2} + |l - \frac{3}{2} - \frac{p}{2}|) \Gamma_{\mathbb{C}}(3s + l - \frac{l_1}{2} - \frac{1}{2} - \frac{q}{2})} & \text{if } \tau = \mathcal{D}_{p,\frac{q}{2}}, p \geq 1, \\ \frac{a_{l_1,p,q}^+ D^{-3s-\frac{l}{2}+\frac{q}{2}} 2^{q-1-l+\frac{l_1}{2}+u} \pi^{1+\frac{q}{2}+\frac{l_1}{2}} \Gamma_{\mathbb{C}}(3s + \frac{1}{2} - \frac{q}{2} + u)}{(3s + \frac{l+|l-l_1|}{2} - \frac{1}{2} - \frac{q}{2}) \Gamma_{\mathbb{C}}(3s + l - \frac{l_1}{2} - \frac{1}{2} - \frac{q}{2})} & \text{if } \tau = \beta_1 \times \beta_2. \end{cases}$$

**Remarks:** a) The factor  $Y_{l,l_1,p,q}(s)$  is of the form  $D^{-3s}$  times a rational function in  $s$ .

b) For  $l = l_1$  we recover Theorem 4.4.1 of [45]. We point out that in our present approach the number  $l_1$  (the  $\mathrm{GL}_2$  weight) can be chosen independently of  $l$  (the  $\mathrm{GSp}_4$  weight), including the case of different parity.

c) In one of our later applications, the number  $D$  will be a fundamental discriminant satisfying  $D \equiv 0 \pmod{4}$  or  $D \equiv 3 \pmod{4}$ . Having the above theorem available for the two cases of  $S$  in (121) assures that  $S$  can be chosen to be a half-integral matrix.

**2.2.3 Corollary.** Let all hypotheses be as in Theorem 2.2.2. Let  $W^\# \in I_W(s, \chi, \chi_0, \tau)$  be the distinguished function defined in table (71). Then

$$Z(s, W^\#, B) = \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s + 1, \chi|_{\mathbb{R}^\times}) L(3s + 1, \tau \times \mathcal{A}\mathcal{I}(\Lambda) \times \chi|_{\mathbb{R}^\times})} Y(s), \quad (124)$$

with

$$Y(s) = \begin{cases} \kappa_{p+1,p} Y_{l,p+1,p,q}(s) & \text{in Case A,} \\ \kappa_{l,p} Y_{l,l,p,q}(s) & \text{in Case B,} \\ \kappa_{l+1,p} Y_{l,l+1,p,q}(s) + \left(3s - \frac{p+q}{2}\right) \kappa_{l-1,p} Y_{l,l-1,p,q}(s) & \text{in Case C.} \end{cases} \quad (125)$$

Here, the constants  $\kappa_{*,p}$  are defined in (69), and the factors  $Y_{l,*p,q}(s)$  are defined in Theorem 2.2.2.

### Tables for archimedean factors

The archimedean Euler factors appearing in (123) can be easily calculated via the archimedean local Langlands correspondence. We omit the details and simply show the results in the following tables. For the principal series case  $\beta_1 \times \beta_2$ , the numbers  $p, q \in \mathbb{C}$  are such that  $\beta_1(a) = a^{\frac{q+p}{2}}$  and  $\beta_2(a) = a^{\frac{q-p}{2}}$ .

$\tau$	$L(s, \pi \times \tilde{\tau})$	$\varepsilon(s, \pi \times \tilde{\tau}, \psi^{-1})$
$\mathcal{D}_{p,\mu}, p \geq 1, \mu \in \mathbb{C}$	$\Gamma_{\mathbb{C}}(s - \mu + \frac{p}{2} + \frac{1}{2}) \Gamma_{\mathbb{C}}(s - \mu + \frac{p}{2} - \frac{1}{2})$ $\Gamma_{\mathbb{C}}(s - \mu + l - \frac{3}{2} + \frac{p}{2}) \Gamma_{\mathbb{C}}(s - \mu +  l - \frac{3}{2} - \frac{p}{2} )$	$i^{2l+3p-3+ 2l-3-p }$
$\beta_1 \times \beta_2$	$\Gamma_{\mathbb{C}}(s + \frac{1-q-p}{2}) \Gamma_{\mathbb{C}}(s + \frac{1-q+p}{2})$ $\Gamma_{\mathbb{C}}(s + l - \frac{q+p+3}{2}) \Gamma_{\mathbb{C}}(s + l - \frac{q-p+3}{2})$	1

The next table shows  $L$ - and  $\varepsilon$ -factors for  $\tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{R}^\times}$ .

$\tau$	$L(s, \tau \times \mathcal{AI}(\Lambda) \times \chi _{\mathbb{R}^\times})$	$\varepsilon(s, \tau \times \mathcal{AI}(\Lambda) \times \chi _{\mathbb{R}^\times}, \psi^{-1})$
$\mathcal{D}_{p,\mu}, p \geq 1, \mu \in \mathbb{C}$	$\Gamma_{\mathbb{C}}(s - \mu + \frac{p}{2})^2$	$(-1)^{p+1}$
$\beta_1 \times \beta_2$	$\Gamma_{\mathbb{C}}(s - \frac{q+p}{2}) \Gamma_{\mathbb{C}}(s - \frac{q-p}{2})$	-1

### 2.3 The global integral representation

Let  $F$  be an algebraic number field and  $\mathbb{A}_F$  its ring of adeles. We fix a non-trivial character of  $F \backslash \mathbb{A}_F$ . Let  $L$  be a quadratic field extension of  $F$ ; the extension  $L/F$  defines the unitary group  $G_2$ . The Eisenstein series  $E(h, s)$  entering into the global integral (131) below will be defined from a section in a global induced representation of  $G_2(\mathbb{A}_F)$ . We therefore start by discussing various models of such induced representations.

#### Global induced representations

Let  $(\tau, V_\tau)$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A}_F)$ . Let  $\chi_0$  be a character of  $L^\times \backslash \mathbb{A}_L^\times$  such that the restriction of  $\chi_0$  to  $\mathbb{A}_F^\times$  concides with  $\omega_\tau$ , the central character of  $\tau$ . Then, as in (21) in the local case,  $\chi_0$  can be used to extend  $\tau$  to a representation of  $M^{(2)}(\mathbb{A}_F)$ , denoted by  $\chi_0 \times \tau$ . Let  $\chi$  be another character of  $L^\times \backslash \mathbb{A}_L^\times$ , considered as a character of  $M^{(1)}(\mathbb{A}_F)$ . This data defines a family of induced representations  $I(s, \chi, \chi_0, \tau)$  of  $G_2(\mathbb{A}_F)$  depending on a complex parameter  $s$ . The space of  $I(s, \chi, \chi_0, \tau)$  consists of functions  $\varphi : G_2(\mathbb{A}_F) \rightarrow V_\tau$  with the transformation property

$$\varphi(m_1 m_2 n g) = \delta_P(m_1 m_2)^{s+1/2} \chi(m_1)(\chi_0 \times \tau)(m_2) \varphi(g)$$

for all  $m_1 \in M^{(1)}(\mathbb{A}_F)$ ,  $m_2 \in M^{(2)}(\mathbb{A}_F)$  and  $n \in N(\mathbb{A}_F)$ . Since the representation  $\tau$  is given as a space of automorphic forms, we may realize  $I(s, \chi, \chi_0, \tau)$  as a space of  $\mathbb{C}$ -valued functions on  $G_2(\mathbb{A}_F)$ . More precisely, to each  $\varphi$  as above we may attach the function  $f_\varphi$  on  $G_2(\mathbb{A}_F)$  given by  $f_\varphi(g) = (\varphi(g))(1)$ . Each function  $f_\varphi$  has the property that  $\mathrm{GL}_2(\mathbb{A}_F) \ni h \mapsto f_\varphi(hg)$  is an element of  $V_\tau$ , for each  $g \in G_2(\mathbb{A}_F)$ . Let  $I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$  be the model of  $I(s, \chi, \chi_0, \tau)$  thus obtained. A third model of the same representation is obtained by attaching to  $f \in I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$  the function

$$W_f(g) = \int_{F \backslash \mathbb{A}_F} f \left( \begin{bmatrix} 1 & & \\ & 1 & x \\ & & 1 \end{bmatrix} g \right) \psi(cx) dx, \quad g \in G_2(\mathbb{A}_F). \quad (126)$$

Here,  $c \in F^\times$  is a fixed element. The map  $f \mapsto W_f$  is injective since  $\tau$  is cuspidal. Let  $I_W(s, \chi, \chi_0, \tau)$  be the space of all functions  $W_f$ . Now write  $\tau \cong \otimes \tau_v$  with local representations  $\tau_v$  of  $\mathrm{GL}_2(F_v)$ . We also factor  $\chi = \otimes \chi_v$  and  $\chi_0 = \otimes \chi_{0,v}$ , where  $\chi_v$  and  $\chi_{0,v}$  are characters of  $\prod_{w|v} L_w^\times$ . Then there are isomorphisms

$$\begin{array}{ccc} I(s, \chi, \chi_0, \tau) & \xrightarrow{\sim} & \otimes_v I(s, \chi_v, \chi_{0,v}, \tau_v) \\ \sim \downarrow & & \downarrow = \\ I_{\mathbb{C}}(s, \chi, \chi_0, \tau) & \xrightarrow{\sim} & \otimes_v I(s, \chi_v, \chi_{0,v}, \tau_v) \\ \sim \downarrow & & \downarrow \sim \\ I_W(s, \chi, \chi_0, \tau) & \xrightarrow{\sim} & \otimes_v I_W(s, \chi_v, \chi_{0,v}, \tau_v) \end{array} \quad (127)$$

Here, the local induced representation  $I(s, \chi_v, \chi_{0,v}, \tau_v)$  consists of functions taking values in a model  $V_{\tau_v}$  of  $\tau_v$ ; see Sect. 1.1 for the precise definition. Assume that  $V_{\tau_v} = \mathcal{W}(\tau_v, \psi_v^{-\mathbf{c}})$  is the Whittaker model of  $V_{\tau_v}$  with respect to the additive character  $\psi_v^{-\mathbf{c}}$ . If we attach to each  $f_v \in I(s, \chi_v, \chi_{0,v}, \tau_v)$  the function  $W_{f_v}(g) = f_v(g)(1)$ , then we obtain the model  $I_W(s, \chi_v, \chi_{0,v}, \tau_v)$  of the same induced representation. The bottom isomorphism in diagram (127) is such that if  $W_v \in I_W(s, \chi_v, \chi_{0,v}, \tau_v)$  are given, with the property that  $W_v|_{G_2(\mathfrak{o}_v)} = 1$  for almost all  $v$ , then the corresponding element of  $I_W(s, \chi, \chi_0, \tau)$  is the function

$$W(g) = \prod_{v \leq \infty} W_v(g_v), \quad g = (g_v)_v \in G_2(\mathbb{A}_F). \quad (128)$$

### The global integral and the basic identity

Now let  $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}, S, L, \Lambda$  be as in Sect. 2.1. Let  $(\pi, V_\pi)$  be a cuspidal, automorphic representation of  $H(\mathbb{A}_F)$  which has a global Bessel model of type  $(S, \Lambda, \psi)$ . Let further  $(\tau, V_\tau)$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A}_F)$ , extended to a representation of  $M^{(2)}(\mathbb{A}_F)$  via a character  $\chi_0$  of  $L^\times \backslash \mathbb{A}_L^\times$ . Define the character  $\chi$  of  $L^\times \backslash \mathbb{A}_L^\times$  by

$$\chi(y) = \Lambda(\bar{y})^{-1} \chi_0(\bar{y})^{-1}, \quad y \in \mathbb{A}_L^\times. \quad (129)$$

Let  $f(g, s)$  be an analytic family in  $I_C(s, \chi, \chi_0, \tau)$ . For  $\mathrm{Re}(s)$  large enough we can form the Eisenstein series

$$E(g, s; f) = \sum_{\gamma \in P(F) \backslash G_2(F)} f(\gamma g, s). \quad (130)$$

In fact,  $E(g, s; f)$  has a meromorphic continuation to the entire complex plane. In [15] Furusawa studied integrals of the form

$$Z(s, f, \phi) = \int_{H(F)Z_H(\mathbb{A}_F) \backslash H(\mathbb{A}_F)} E(h, s; f) \phi(h) dh, \quad (131)$$

where  $\phi \in V_\pi$ . Theorem (2.4) of [15], the ‘‘Basic Identity’’, states that

$$Z(s, f, \phi) = Z(s, W_f, B_\phi) := \int_{R(\mathbb{A}_F) \backslash H(\mathbb{A}_F)} W_f(\eta h, s) B_\phi(h) dh, \quad \eta \text{ as in (5)}. \quad (132)$$

where  $R(\mathbb{A}_F)$  is the Bessel subgroup determined by  $(S, \Lambda, \psi)$ , and  $B_\phi$  is the Bessel function corresponding to  $\phi$ ; see (98). The function  $W_f(\cdot, s)$  appearing in (132) is the element of  $I_W(s, \chi, \chi_0, \tau)$  corresponding to  $f(\cdot, s) \in I_C(s, \chi, \chi_0, \tau)$ ; see (126) for the formula relating  $f$  and  $W_f$ .

The importance of the basic identity lies in the fact that the integral on the right side of (132) is Eulerian. Namely, assume that  $f(\cdot, s)$  corresponds to a pure tensor  $\otimes f_v$  via the middle isomorphism in (127). Assume that  $W_v \in I_W(s, \chi_v, \chi_{0,v}, \tau_v)$  corresponds to  $f_v \in I(s, \chi_v, \chi_{0,v}, \tau_v)$ . Then

$$W_f(g, s) = \prod_{v \leq \infty} W_v(g_v, s), \quad g = (g_v)_v \in G_2(\mathbb{A}_F),$$

see (128). Assume further that the global Bessel function  $B_\phi$  factorizes as in (99). Then it follows from (132) that

$$Z(s, f, \phi) = \prod_{v \leq \infty} Z_v(s, W_v, B_v), \quad (133)$$

with the local zeta integrals

$$Z_v(s, W_v, B_v) = \int_{R(F_v) \backslash H(F_v)} W_v(\eta h, s) B_v(h) dh. \quad (134)$$

Furusawa has calculated the local integrals (134) in the case where all the data is unramified. In our non-archimedean Theorem 2.2.1 we calculated these integrals in the case where the  $\mathrm{GSp}_4$  data is still unramified, but the  $\mathrm{GL}_2$  data is arbitrary. Here, we took for  $W_v$  the distinguished vector  $W^\#$  from Corollary 1.2.4. In our archimedean Corollary 2.2.3 we calculated these integrals in the case where the  $\mathrm{GSp}_4$  data is a scalar minimal  $K$ -type lowest weight representation, and the  $\mathrm{GL}_2$  data is arbitrary. Here, we took for  $W_v$  the distinguished vector  $W^\#$  defined in table (71).

### The global integral representation over $\mathbb{Q}$

The important fact in the theory outlined above is that the local functions  $W_v$  can be chosen such that the integrals (134) are all non-zero. We have to make sure, however, that the data entering the local theorems, in particular the characters  $\chi$ ,  $\chi_0$  and  $\Lambda$ , fit into a global situation. For simplicity, we assume from now on that the number field is  $F = \mathbb{Q}$  (this, however, is not essential).

**2.3.1 Lemma.** *Let  $L$  be an imaginary quadratic field extension of  $\mathbb{Q}$ . Let  $\omega = \otimes \omega_p$  be a character of  $\mathbb{Q}^\times \backslash \mathbb{A}^\times$ . Let  $l_2$  be an integer such that  $(-1)^{l_2} = \omega_\infty(-1)$ . Then there exists a character  $\chi_0 = \otimes \chi_{0,v}$  of  $L^\times \backslash \mathbb{A}_L^\times$  such that*

- i) the restriction of  $\chi_0$  to  $\mathbb{A}^\times$  coincides with  $\omega$ , and
- ii)  $\chi_{0,\infty}(\zeta) = \zeta^{l_2}$  for all  $\zeta \in S^1$ .

**Proof.** Since  $\omega$  is trivial on  $L^\times \cap \mathbb{A}^\times = \mathbb{Q}^\times$ , we can extend  $\omega$  to a character of  $L^\times \mathbb{A}^\times$  in such a way that  $\omega|_{L^\times} = 1$ . Since  $S^1 \cap (L^\times \mathbb{A}^\times) = \{\pm 1\}$ , we can further extend  $\omega$  to a character of  $S^1 L^\times \mathbb{A}^\times$  in such a way that  $\omega(\zeta) = \zeta^{l_2}$  for all  $\zeta \in S^1$ . For each finite place  $v$  of  $L$  we will choose a compact subgroup  $U_v$  of  $\mathfrak{o}_{L,v}^\times$  such that  $\omega$  can be extended to  $S^1 L^\times \mathbb{A}^\times (\prod_{v < \infty} U_v)$ , with  $\omega$  trivial on  $\prod_{v < \infty} U_v$  and  $U_v = \mathfrak{o}_{L,v}^\times$  for almost all  $v$ . Hence, the  $U_v$  should be chosen such that  $\omega$  is trivial on  $(\prod_{v < \infty} U_v) \cap S^1 L^\times \mathbb{A}^\times$ . We consider the intersection

$$\left( \prod_{v < \infty} U_v \right) \cap S^1 L^\times \mathbb{A}^\times = \left( \prod_{v < \infty} U_v \right) \cap \mathbb{C}^\times L^\times \left( \prod_{p < \infty} \mathbb{Z}_p^\times \right). \quad (135)$$

Let  $zax$  be an element of this intersection, where  $z \in \mathbb{C}^\times$ ,  $a \in L^\times$  and  $x \in \prod_{p < \infty} \mathbb{Z}_p^\times$ . We have  $a \in L^\times \cap \prod_{v < \infty} \mathfrak{o}_{L,v}^\times = \mathfrak{o}_L^\times$ , which is a finite set, say  $\{a_1, \dots, a_m\}$ . For  $i$  such that  $a_i \notin \mathbb{Q}$ , choose a prime  $p$  such that  $a_i \notin \mathbb{Z}_p^\times$ . Then choose a place  $v$  lying above  $p$ , and choose  $U_v$  so small that  $a_i \notin U_v \mathbb{Z}_p^\times$ . Then the intersection (135) equals

$$\left( \prod_{v < \infty} U_v \right) \cap \mathbb{C}^\times \mathbb{Q}^\times \left( \prod_{p < \infty} \mathbb{Z}_p^\times \right). \quad (136)$$

We can choose  $U_v$  even smaller, so that  $\omega$  is trivial on this intersection. We can therefore extend  $\omega$  to a character of

$$S^1 L^\times \mathbb{A}^\times \left( \prod_{v < \infty} U_v \right) = \mathbb{C}^\times L^\times \left( \prod_{v < \infty} U_v \right) \left( \prod_{p < \infty} \mathbb{Z}_p^\times \right). \quad (137)$$

in such a way that  $\omega$  is trivial on  $\prod_{v<\infty} U_v$ . The group (137) is of finite index in  $\mathbb{C}^\times L^\times(\prod_{v<\infty} \mathfrak{o}_{L,v}^\times)$ , and therefore of finite index in  $\mathbb{A}_L^\times$  (using the finiteness of the class number). By Pontrjagin duality, we can now extend  $\omega$  to a character  $\chi_0$  of  $\mathbb{A}_L^\times$  with the desired properties. ■

We now explain the setup for the global integral representation. For simplicity we will work over the rational numbers. We require the following ingredients.

- $\psi = \prod_v \psi_v$  is a character of  $\mathbb{Q} \backslash \mathbb{A}$  such that  $\psi_\infty(x) = e^{-2\pi i x}$ . Also, we require that  $\psi_p$  has conductor  $\mathbb{Z}_p$  for all finite  $p$ . There is exactly one such character  $\psi$ .
- Let  $D > 0$  be a fundamental discriminant, and define  $\mathbf{a}, \mathbf{b}, \mathbf{c} \in \mathbb{Q}$  and the matrix  $S$  by

$$S = S(-D) := \begin{bmatrix} \mathbf{a} & \mathbf{b}/2 \\ \mathbf{b}/2 & \mathbf{c} \end{bmatrix} = \begin{cases} \begin{bmatrix} D/4 & \\ & 1 \end{bmatrix} & \text{if } D \equiv 0 \pmod{4}, \\ \begin{bmatrix} (1+D)/4 & 1/2 \\ 1/2 & 1 \end{bmatrix} & \text{if } D \equiv 3 \pmod{4}. \end{cases} \quad (138)$$

- Let  $L$  be the imaginary quadratic field  $\mathbb{Q}(\sqrt{-D})$ . The unitary groups  $G_i$  are defined with respect to the extension  $L/\mathbb{Q}$ .
- Let  $\pi = \otimes \pi_v$  be a cuspidal, automorphic representation of  $H(\mathbb{A})$  with the following properties. The archimedean component  $\pi_\infty$  is a (limit of) discrete series representation with minimal  $K$ -type  $(l, l)$ , where  $l \geq 2$ , and trivial central character. If  $v$  is a non-archimedean place, then  $\pi_v$  is unramified and has trivial central character.
- Let  $\tau = \otimes \tau_v$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  with central character  $\omega_\tau$ .
- Let  $\chi_0$  be a character of  $L^\times \backslash \mathbb{A}_L^\times$  such that  $\chi_0|_{\mathbb{A}^\times} = \omega_\tau$  and  $\chi_{0,\infty}(\zeta) = \zeta^{l_2}$  for  $\zeta \in S^1$ . Here,  $l_2$  is any integer of the same parity as the weights of  $\tau$ . Such a character exists by Lemma 2.3.1.
- Let  $\Lambda = \otimes \Lambda_v$  be a character of  $L^\times \backslash \mathbb{A}_L^\times$  such that  $\Lambda_\infty = 1$  and such that  $\Lambda_v$  is unramified for all finite  $v$ . Hence,  $\Lambda$  is a character of the ideal class group

$$\left( L^\times \mathbb{C}^\times \left( \prod_{v \nmid \infty} \mathfrak{o}_v^\times \right) \right) \backslash \mathbb{A}_L^\times. \quad (139)$$

- Let  $\chi$  be the character of  $\mathbb{A}_L^\times$  defined by (129).

Let  $l_1$  be any weight occurring in  $\tau_\infty$ . Let  $\Psi$  be the unique cusp form in the space of  $\tau$  that is a newform at all non-archimedean places, corresponds to a vector of weight  $l_1$  at the archimedean place and is normalized so that the corresponding Whittaker function

$$W_\Psi(g) = \int_{\mathbb{Q} \backslash \mathbb{A}} \Psi \left( \begin{bmatrix} 1 & x \\ & 1 \end{bmatrix} g \right) \psi(x) dx \quad (140)$$

satisfies  $W_\Psi \left( \begin{bmatrix} t^+ & \\ & 1 \end{bmatrix} \right) = 1$ , where  $t^+$  is the positive real number chosen in (64), considered as an idele with trivial non-archimedean components. We can extend  $\Psi$  to a function on  $G_1(\mathbb{A})$  via  $\Psi(ag) = \chi_0(a)\Psi(g)$  for  $a \in \mathbb{A}_L^\times$ ,  $g \in \mathrm{GL}_2(\mathbb{A})$ . Let us explicitly describe a section  $f_{[l_1-l], l_2, l_1}(g, s) \in$

$I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$ . For a non-archimedean place  $v$ , let  $\tau_v$  have conductor  $\mathfrak{p}^n$  and let  $J_v$  be the function on  $K_v^{G_2} = G_2(\mathfrak{o}_v)$  defined by

$$J_v(k) = \begin{cases} 1 & \text{if } k \in P(\mathfrak{o})\eta_0 K^H \Gamma(\mathfrak{P}^n), \\ 0 & \text{otherwise} \end{cases} \quad (141)$$

(see (34) for the definition of  $\eta_0$ ). For  $n = 0$  this is the characteristic function of  $K_v^{G_2}$ . Define

$$J_{|l_1-l|, l, l_2, l_1}(k, s) = \Phi_{|l_1-l|, l, l_2, l_1}^\#(k_\infty, s) \cdot \prod_{v<\infty} J_v(k_v), \quad \text{where } k = (k_v)_v \in \prod_v K_v^{G_2};$$

see (62). Finally, let

$$f_{|l_1-l|, l, l_2, l_1}(g, s) = \delta_P(m_1 m_2)^{s+\frac{1}{2}} \chi(m_1) \Psi(m_2) J_{|l_1-l|, l, l_2, l_1}(k, s) \quad (142)$$

for  $g = m_1 m_2 n k$  with  $m_1 \in M^{(1)}(\mathbb{A})$ ,  $m_2 \in M^{(2)}(\mathbb{A})$ ,  $n \in N(\mathbb{A})$ ,  $k \in \prod_v K_v^{G_2}$ . It is easy to see that  $f = f_{|l_1-l|, l, l_2, l_1}$  belongs to  $I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$  and that  $(W_f)_v$  corresponds to the vector in Corollary 1.2.4 if  $v$  is non-archimedean, and to the vector  $W_{|l_1-l|, l, l_2, l_1}^\#$  given by (67) if  $v = \infty$ . In view of Theorem 2.2.1 and Corollary 2.2.3, the following important result is now immediate.

**2.3.2 Theorem. (Global Integral Representation)** Let  $\psi, D, S$  and  $\pi, \tau, \chi_0, \chi, \Lambda$  be as above. Let  $f = f_{|l_1-l|, l, l_2, l_1}$  be the section in  $I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$  defined above, and  $\phi = \otimes \phi_v$  be a vector in the space of  $\pi$  such that  $\phi_v$  is unramified for all finite  $v$  and such that  $\phi_\infty$  is a vector of weight  $(-l, -l)$  in  $\pi_\infty$ . Then the global zeta integral  $Z(s, f, \phi)$  defined in (131) is given by

$$Z(s, f, \phi) = \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s + 1, \chi|_{\mathbb{A}^\times}) L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})} \cdot B_\phi(1) \cdot Y_{l, l_1, p, q}(s) \cdot \prod_{v<\infty} Y_v(s), \quad (143)$$

with  $B_\phi$  as in (98), with the factors  $Y_v(s)$  for non-archimedean  $v$  given by Theorem 2.2.1, and with the archimedean factor  $Y_{l, l_1, p, q}(s)$  given by Theorem 2.2.2. In (143),  $\tilde{\pi}$  and  $\tilde{\tau}$  denote the contragredient of  $\pi$  and  $\tau$ , respectively. The symbol  $\mathcal{AI}(\Lambda)$  stands for the  $\mathrm{GL}_2(\mathbb{A})$  representation attached to the character  $\Lambda$  of  $\mathbb{A}_L^\times$  via automorphic induction, and  $L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})$  is a standard  $L$ -factor for  $\mathrm{GL}_2 \times \mathrm{GL}_2 \times \mathrm{GL}_1$ .

Next, we state a second version of the above theorem where we choose the distinguished vector at all places, including the archimedean ones. Recall the Cases A,B,C defined in (70). Let  $l_2$  be as in Theorem 1.5.1. The following result is also an immediate consequence of Theorem 2.2.1 and Corollary 2.2.3 and will be key for the functional equation.

**2.3.3 Theorem.** Let  $\psi, D, S$  and  $\pi, \tau, \chi_0, \chi, \Lambda$  be as above. Let  $B_v$  be the unramified Bessel function given by formula (102) if  $v$  is non-archimedean, and let  $B_v$  be the function defined in (105) if  $v$  is archimedean. Let  $W_v^\#(\cdot, s)$  be as in Corollary 1.2.4 if  $v$  is non-archimedean, and as in table (71) if  $v$  is archimedean. Let

$$W^\#(g, s) = \prod_v W_v^\#(g_v, s), \quad B(h) = \prod_v B_v(h_v),$$

for  $g = (g_v)_v \in G_2(\mathbb{A})$  and  $h = (h_v)_v \in H(\mathbb{A})$ . Then the global zeta integral  $Z(s, W^\#, B)$  defined in (132) is given by

$$Z(s, W^\#, B) = \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s + 1, \chi|_{\mathbb{A}^\times}) L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})} Y(s), \quad (144)$$

where  $Y(s) = \prod_v Y_v(s)$ , a finite product, with the local factors given in Theorem 2.2.1 (non-archimedean case) and Corollary 2.2.3 (archimedean case).

## 2.4 The functional equation

In this section we prove that, in the setting of Theorem 2.3.3, the global  $L$ -function  $L(s, \pi \times \tau)$  satisfies the expected functional equation. We begin with some local preparations.

### The factor $X(s)$

Assume that  $F$  is a non-archimedean local field of characteristic zero, or  $F = \mathbb{R}$ . Let  $\tau, \chi, \chi_0, \Lambda$  and  $\pi$  be as in Theorem 2.2.1 (non-archimedean case) and Theorem 2.2.2 (archimedean case). We will calculate the function

$$X(s) = K(s) \frac{L(6s+1, \chi|_{F^\times}) L(3s+1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})}{L(6s, \chi|_{F^\times}) L(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})} \\ \times \varepsilon(6s, \chi|_{F^\times}, \psi^{-1}) \varepsilon(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times}, \psi^{-1}) \frac{\hat{Y}(-s)}{Y(s)}, \quad (145)$$

which will be relevant for the functional equation. Here,  $K(s)$  is the factor resulting from the local intertwining operator, defined in (30) and explicitly given in Proposition 1.4.1 (non-archimedean case with  $n = 0$ ), Theorem 1.4.2 (non-archimedean case with  $n > 0$ ) and Theorem 1.5.1 (archimedean case). The factor  $Y(s)$  results from the local zeta integral calculation and is given in Theorem 2.2.1 (non-archimedean case) and Corollary 2.2.3 (archimedean case). The factor  $\hat{Y}(s)$  is similar to  $Y(s)$ , but with the data  $(\chi, \chi_0, \tau)$  replaced by  $(\bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ .

**2.4.1 Lemma.** *Assume that  $F$  is  $p$ -adic. Let  $\delta$  be the valuation of the discriminant of  $L/F$  if  $L/F$  is a ramified field extension, and  $\delta = 0$  otherwise. Let  $X(s)$  be as in (145). Let  $\mathfrak{p}^n$  be the conductor of  $\tau$ . Assume that the restriction of  $\Lambda$  to  $F^\times$  is trivial<sup>2</sup>, so that  $\chi|_{F^\times} = \omega_\tau^{-1}$ .*

i) If  $\tau = \beta_1 \times \beta_2$  with unramified characters  $\beta_1$  and  $\beta_2$  of  $F^\times$ , then

$$X(s) = \chi(\varpi)^\delta \chi_{L/F}(-1) q^{-6\delta s}. \quad (146)$$

ii) If  $L/F$  is an unramified field extension or  $L = F \oplus F$ , then

$$X(s) = \omega_\tau(c^2/d) \varepsilon(1/2, \tilde{\tau}, \psi^{-1})^4 q^{-12ns}. \quad (147)$$

**Proof.** i) By Proposition 1.4.1,

$$X(s) = q^{-\delta} \varepsilon(6s, \chi|_{F^\times}, \psi^{-1}) \varepsilon(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times}, \psi^{-1}) \frac{\hat{Y}(-s)}{Y(s)}.$$

For unramified  $\tau$  we have  $Y(s) = 1$ , and the character  $\chi|_{F^\times}$  is unramified. Hence

$$X(s) = q^{-\delta} \varepsilon(3s, \chi \tau \times \mathcal{AI}(\Lambda), \psi^{-1}) = \chi(\varpi)^\delta \chi_{L/F}(-1) q^{-6\delta s}.$$

ii) In the case of  $\tau$  being a spherical representation, (147) follows from (146). We may therefore assume that  $n > 0$ . Using standard properties of the  $\varepsilon$ -factors, we can check that

$$\varepsilon(6s, \chi|_{F^\times}, \psi^{-1}) \varepsilon(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times}, \psi^{-1})$$

---

<sup>2</sup>If the  $\mathrm{GSp}_4(F)$  representation  $\pi$  has a  $(S, \Lambda, \psi)$  Bessel model, this means that the central character of  $\pi$  is trivial.

equals

$$\chi_{L/F}(\varpi)^n q^{-(6s-1)(n+a(\omega_\tau))-\frac{a(\omega_\tau)}{2}} \varepsilon\left(\frac{1}{2}, \chi|_{F^\times}, \psi^{-1}\right) \varepsilon\left(\frac{1}{2}, \tilde{\tau}, \psi^{-1}\right).$$

Now the lemma follows directly from Theorem 1.4.2 and Theorem 2.2.1. We note here that, in the case under consideration, we have  $n > 0$  and  $(\frac{L}{\mathfrak{p}}) = \pm 1$ , so that  $Y(s) = L(6s+1, \chi|_{F^\times})$ . ■

**2.4.2 Lemma.** Assume that  $F = \mathbb{R}$ . Let  $X(s)$  be as in (145). Assume that  $\pi$  is the lowest weight representation of  $\mathrm{PGSp}_4(\mathbb{R})$  with scalar minimal  $K$ -type  $(l, l)$ , where  $l \geq 2$ . We assume that  $\Lambda = 1$ , so that  $\chi|_{\mathbb{R}^\times} = \omega_\tau^{-1}$ . Then

$$X(s) = -\omega_\tau(-D)^{-1} \varepsilon(s, \tilde{\pi} \times \tilde{\tau}, \psi^{-1}) D^{6s}.$$

**Proof.** The ingredients in the definition (145) of the  $X$ -factor are all known; see Theorem 1.5.1 for the factor  $K(s)$ , Corollary 2.2.3 for the factor  $Y(s)$ , and the tables in Sect. 2.2 for the  $L$ - and  $\varepsilon$ -factors of  $\tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{R}^\times}$  and  $\tilde{\pi} \times \tilde{\tau}$ . The asserted formula is then obtained by going through the various possibilities for the type of representation  $\tau$  and the parity of  $l$ , substituting the ingredients and simplifying. This is where Lemma 1.3.8 is used. We omit the details. ■

### The global functional equation

We can now prove the global functional equation for many of the  $L$ -functions  $L(s, \pi \times \tau)$ , provided that the  $\mathrm{GSp}_4$  representation  $\pi$  is of the type considered before and has an appropriate global Bessel model. Once we complete the transfer to  $\mathrm{GL}_4$ , we will be able to remove all restrictions on the  $\mathrm{GL}_2$  representation  $\tau$ ; see Theorem 5.2.2.

**2.4.3 Theorem. (Functional Equation)** Assume that the positive integer  $D$  is such that  $-D$  is the discriminant of the number field  $L := \mathbb{Q}(\sqrt{-D})$ . Let  $S(-D)$  be as in (138). Let  $\Lambda = \otimes \Lambda_v$  be a character of  $L^\times \backslash \mathbb{A}_L^\times$  such that  $\Lambda_\infty = 1$  and such that  $\Lambda_v$  is unramified for all finite places  $v$ . Let  $\pi = \otimes \pi_v$  be a cuspidal, automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$  with the following properties.

- i)  $\pi$  has trivial central character;
- ii) There exists an integer  $l \geq 2$  such that  $\pi_\infty$  is the (limit of) discrete series representation of  $\mathrm{PGSp}_4(\mathbb{R})$  with scalar minimal  $K$ -type  $(l, l)$ ;
- iii)  $\pi_p$  is unramified for all primes  $p$ ;
- iv)  $\pi$  has a global Bessel model of type  $(S(-D), \Lambda, \psi)$  (see Sect. 2.1).

Let  $\tau = \otimes \tau_v$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  such that  $\tau_p$  is unramified for the primes  $p$  dividing  $D$ . Then  $L(s, \pi \times \tau)$  has meromorphic continuation to all of  $\mathbb{C}$  and satisfies the functional equation

$$L(s, \pi \times \tau) = \varepsilon(s, \pi \times \tau) L(1-s, \tilde{\pi} \times \tilde{\tau}). \quad (148)$$

Here,  $\varepsilon(s, \pi \times \tau) = \prod_v \varepsilon(s, \pi_v \times \tau_v, \psi_v^{-1})$ , and the local  $\varepsilon$ -factors are the ones attached to  $\pi_v \times \tau_v$  via the local Langlands correspondence.

**Remark:** The hypothesis on  $\tau$  will be removed later; see Theorem 5.2.2 for a statement where  $\tau$  is any cuspidal representation on any  $\mathrm{GL}_n$ .

**Proof.** Note that  $D = -\mathbf{d}$ . Let the characters  $\chi_0, \chi$  and  $\Lambda$  of  $L^\times \backslash \mathbb{A}_L^\times$  be as in Theorem 2.3.3. Let  $f = \otimes f_v \in I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$  be the function corresponding to the distinguished vector  $W^\# = \otimes W_v^\#$ ; see the diagram (127). Let  $E(g, s; f)$  be the Eisenstein series defined in (130). By the general theory of Eisenstein series,

$$E(g, s; f) = E(g, -s; M(s)f), \quad (149)$$

where  $M(s)$  is the global intertwining operator given by a formula similar to (28) in the local case. Note that the Eisenstein series on the right hand side of (149) is defined with respect to the data  $(\bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$  instead of  $(\chi, \chi_0, \tau)$ ; see (29). By our uniqueness results Corollary 1.2.4 and Corollary 1.3.7, and the explicit archimedean calculations resulting in Theorem 1.5.1,

$$M(s)f(\cdot, s, \chi, \chi_0, \tau) = K(s)f(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau), \quad (150)$$

where  $K(s) = \prod_v K_v(s)$ , and the local functions  $K_v(s)$  are the same as in (30). Hence

$$E(g, s; f) = K(s)E(g, -s; \hat{f}), \quad (151)$$

where  $\hat{f}$  abbreviates  $f(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ . For the global zeta integrals defined in (131) it follows that

$$Z(s, f, \phi) = K(s)Z(-s, \hat{f}, \phi). \quad (152)$$

By the basic identity (132),

$$Z(s, W^\#, B_\phi) = K(s)Z(-s, \hat{W}^\#, B_\phi), \quad (153)$$

where  $\hat{W}^\#$  abbreviates  $W^\#(\cdot, -s, \bar{\chi}^{-1}, \chi \bar{\chi} \chi_0, \chi \tau)$ . Now we let  $B_\phi$  be the distinguished Bessel vector as in Theorem 2.3.3, and apply this theorem to both sides of (153). The result is

$$\begin{aligned} & \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s + 1, \chi|_{\mathbb{A}^\times})L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})} Y(s) \\ &= K(s) \frac{L(-3s + \frac{1}{2}, \tilde{\pi} \times \widetilde{\chi \tau})}{L(-6s + 1, \chi^{-1}|_{\mathbb{A}^\times})L(-3s + 1, \chi \tau \times \mathcal{AI}(\Lambda) \times \chi^{-1}|_{\mathbb{A}^\times})} \hat{Y}(-s). \end{aligned} \quad (154)$$

Note that  $\Lambda(\zeta) = \chi_0(\zeta)^{-1}\chi(\bar{\zeta})^{-1}$ , and this character does not change under  $(\chi, \chi_0) \mapsto (\bar{\chi}^{-1}, \chi \bar{\chi} \chi_0)$ . However, since  $\Lambda^{-1} = \bar{\Lambda}$ , we have  $\mathcal{AI}(\Lambda) = \mathcal{AI}(\bar{\Lambda}) = \mathcal{AI}(\Lambda^{-1})$ . Using  $\chi \tau \cong \tilde{\tau}$  and the global functional equations for characters and for representations of  $\mathrm{GL}_2 \times \mathrm{GL}_2$  (see [27]), we can rewrite (154) as

$$\begin{aligned} & \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(-3s + \frac{1}{2}, \tilde{\pi} \times \tau)} = K(s) \frac{L(6s + 1, \chi|_{\mathbb{A}^\times})L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})}{L(6s, \chi|_{\mathbb{A}^\times})L(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times})} \\ & \quad \times \varepsilon(6s, \chi|_{\mathbb{A}^\times}) \varepsilon(3s, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{\mathbb{A}^\times}) \frac{\hat{Y}(-s)}{Y(s)} \\ &= \prod_v X_v(s), \end{aligned} \quad (155)$$

with local quantities  $X_v(s)$  as in (145). These quantities were calculated in Lemmas 2.4.1 and 2.4.2. For a prime  $p$  let  $\delta_p$  be the  $p$ -valuation of  $D$ , so that  $D = \prod_p p^{\delta_p}$ . Let  $n_p$  be the conductor of  $\tau_p$ .

Let  $S$  be the finite set of primes  $p$  such that  $\tau_p$  is not unramified. By hypothesis, if  $p \in S$ , then  $p \nmid D$ , i.e.,  $L_p/\mathbb{Q}_p$  is not a ramified field extension. Using Lemmas 2.4.1 and 2.4.2, and the fact that  $\varepsilon(s, \tilde{\pi}_p \times \tilde{\tau}_p, \psi_p^{-1}) = \varepsilon(s, \tilde{\tau}_p, \psi_p^{-1})^4$  for all finite places  $p$ , a straightforward calculation shows that

$$\prod_v X_v(s) = \varepsilon(3s + 1/2, \tilde{\pi} \times \tilde{\tau}).$$

Replacing  $s$  by  $\frac{1}{3}s - \frac{1}{6}$  and  $\tau$  by  $\tilde{\tau}$ , and observing that  $\pi$  is self-contragredient, we obtain the claim of the theorem. ■

### 3 The pullback formula

In this section, we prove a second integral representation for our  $L$ -function. This is achieved via the ‘‘pullback formula’’, which expresses the (relatively complicated) Eisenstein series  $E(g, s; f)$ , defined in (130), as the inner product of an automorphic form in the space of  $\tau$  with the pullback of a simple Siegel-type Eisenstein series on  $G_3$ .

We will first prove a local version of the pullback formula. This is the key technical ingredient behind the (global) pullback formula, which, when coupled with the results of the previous sections, will lead to the second integral representation. This will be crucial for proving the entireness of the  $\mathrm{GSp}_4 \times \mathrm{GL}_2$   $L$ -function  $L(s, \pi \times \tau)$ .

#### 3.1 Local sections: non-archimedean case

Let  $F$  be  $p$ -adic. We use the notation from Theorem 1.2.3. In addition, we will assume that  $\Lambda|_{F^\times} = 1$ . We define the principal congruence subgroup

$$\Gamma^{(3)}(\mathfrak{P}^n) = \{g \in G_3(\mathfrak{o}) \mid g \equiv 1 \pmod{\mathfrak{P}^n}\}, \quad (156)$$

and consider the subgroup

$$N_1(\mathfrak{o}) = \iota\left(\begin{bmatrix} 1 & \mathfrak{o} \\ & 1 \end{bmatrix}, 1\right) \quad (157)$$

(see (16) for the definition of the embedding  $\iota$ ). The group  $N_1(\mathfrak{o})$  is normalized by the group

$$\widetilde{R}(\mathfrak{o}) = \left\{ \iota\left(\begin{bmatrix} 1 & \\ & \lambda \end{bmatrix}, h\right) \mid h \in H(\mathfrak{o}), \lambda = \mu_2(h) \right\}.$$

As before, let  $n$  be such that  $\mathfrak{p}^n$  is the conductor of  $\tau$ . Define the congruence subgroup  $C(\mathfrak{P}^n)$  of  $G_3(\mathfrak{o})$  by

$$C(\mathfrak{P}^n) := \widetilde{R}(\mathfrak{o}) N_1(\mathfrak{o}) \Gamma^{(3)}(\mathfrak{P}^n). \quad (158)$$

Note that this is really a group, since  $\Gamma^{(3)}(\mathfrak{P}^n)$  is normal in the maximal compact subgroup  $G_3(\mathfrak{o})$ . We note here an alternate description of  $C(\mathfrak{P}^n)$  that will be useful: It consists of precisely the matrices  $g \in G_3(\mathfrak{o})$  that satisfy

$$g \equiv \begin{bmatrix} \mathfrak{o} & \mathfrak{o} & \mathfrak{o} & \mathfrak{o} \\ \mathfrak{o} & \mathfrak{o} & \mathfrak{o} & \mathfrak{o} \\ & & 1 & \\ \mathfrak{o} & \mathfrak{o} & \mathfrak{o} & \mathfrak{o} \\ \mathfrak{o} & \mathfrak{o} & \mathfrak{o} & \mathfrak{o} \\ & & & \mathfrak{o}^\times \end{bmatrix} \pmod{\mathfrak{P}^n}. \quad (159)$$

We define  $\tilde{\chi}$  to be the character on  $P_{12}$  (see (14)) given by

$$\tilde{\chi}(m(A, v)n) = \chi(v^{-1} \det(A)). \quad (160)$$

For  $s \in \mathbb{C}$ , we form the induced representation

$$I(\tilde{\chi}, s) = \text{Ind}_{P_{12}(F)}^{G_3(F)}(\tilde{\chi} \delta_{12}^s) \quad (161)$$

(see (15)), consisting of smooth functions  $\Xi$  on  $G_3(F)$  such that

$$\Xi(n_0 m(A, v)g, s) = |v|^{-9(s+\frac{1}{2})} |N(\det A)|^{3(s+\frac{1}{2})} \chi(v^{-1} \det A) \Xi(g, s) \quad (162)$$

for  $n_0 \in N_{12}(F)$ ,  $m(A, v) \in M_{12}(F)$ ,  $g \in G_3(F)$ . For any  $t \in L$ , set

$$\Omega(t) := \begin{bmatrix} 1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & \alpha & 1 \\ \bar{\alpha} & & & & 1 \\ \bar{t} & & & & & 1 \end{bmatrix},$$

where  $\alpha$  is the element defined in (4). We define

$$I_L = \begin{cases} \{\varpi^r \mid 0 \leq r \leq n\} & \text{if } (\frac{L}{\mathfrak{p}}) = -1, \\ \{(\varpi^{r_1}, \varpi^{r_2}) \mid 0 \leq r_1, r_2 \leq n\} & \text{if } (\frac{L}{\mathfrak{p}}) = 1, \\ \{\varpi_L^r \mid 0 \leq r \leq 2n\} & \text{if } (\frac{L}{\mathfrak{p}}) = 0. \end{cases}$$

From Lemma 3.1.1 below it follows that there exists, for each  $t \in I_L$ , a unique well-defined section  $\Upsilon_t \in I(\tilde{\chi}, s)$  satisfying all of the following,

- i)  $\Upsilon_t(\Omega(t), s) = 1$ ,
- ii)  $\Upsilon_t(gk, s) = \Upsilon_t(g, s)$  for all  $g \in G_3(F)$ ,  $k \in C(\mathfrak{P}^n)$ ,
- iii)  $\Upsilon_t(g, s) = 0$  if  $g \notin P_{12}(F)\Omega(t)C(\mathfrak{P}^n)$ .

We define  $\Upsilon \in I(\tilde{\chi}, s)$  by

$$\Upsilon = \sum_{t \in I_L} \Upsilon_t. \quad (163)$$

**3.1.1 Lemma.** Let  $A \in \text{GL}_3(F)$ ,  $v \in F^\times$ ,  $n_0 \in N_{12}(F)$  and  $t \in \mathfrak{o}_L$  be such that

$$\Omega(t)^{-1} n_0 m(A, v) \Omega(t) \in C(\mathfrak{P}^n).$$

Then

$$v^{-1} \det(A) \in (1 + \mathfrak{P}^n) \cap \mathfrak{o}_L^\times.$$

**Proof.** Since the statement is trivial for  $n = 0$ , we will assume  $n > 0$ . Let  $P = n_0 m(A, v) = \begin{bmatrix} A & B \\ 0 & v^t \bar{A}^{-1} \end{bmatrix}$  with  $A = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix}$  and  $B = \begin{bmatrix} b_1 & b_2 & b_3 \\ b_4 & b_5 & b_6 \\ b_7 & b_8 & b_9 \end{bmatrix}$ . Note that  $A^{-1}B$  is self-adjoint; however we won't use this. Suppose  $M := \Omega(t)^{-1} n_0 m(A, v) \Omega(t) \in C(\mathfrak{P}^n)$ . This implies that  $A \in \mathrm{GL}_3(\mathfrak{o}_L)$ ,  $v \in \mathfrak{o}^\times$  and  $n_0 \in N_{12}(\mathfrak{o})$ . Let us set  $d := \det(A) \in \mathfrak{o}_L^\times$ . We will use the description given in (159) for a matrix in  $C(\mathfrak{P}^n)$ . Since the  $(1, 6), (2, 6), (3, 4), (3, 5)$  entries of  $M$  are in  $\mathfrak{P}^n$ , we obtain  $b_3, b_6, b_7, b_8 \in \mathfrak{P}^n$ . Looking at the  $(3, 2), (3, 3)$  entries of  $M$ , we obtain  $a_8 \in \mathfrak{P}^n$  and  $a_9 \in 1 + \mathfrak{P}^n$ . Looking at the  $(5, 6)$  entry of  $M$  and using the fact that  $v, d \in \mathfrak{o}_L^\times$  we deduce that  $a_2 a_7 \in \mathfrak{P}^n$ . Calculating the determinant of  $A$  along the third row, we obtain

$$d = a_7(a_2 a_6 - a_3 a_5) - a_8(a_1 a_6 - a_3 a_4) + a_9(a_1 a_5 - a_2 a_4) \equiv a_1 a_5 - a_2 a_4 - a_7 a_3 a_5 \pmod{\mathfrak{P}^n}.$$

Since  $d \in \mathfrak{o}_L^\times$ , it follows that either  $a_2$  or  $a_5$  is a unit. Set

$$g_2 := \begin{bmatrix} a_2 + ab_1 & b_1 \\ -\bar{\alpha}(a_2 + ab_1) - \alpha \bar{a}_2 \frac{v}{d} & -\bar{\alpha}b_1 - \bar{a}_2 \frac{v}{d} \end{bmatrix}, \quad g_5 := \begin{bmatrix} a_5 + ab_4 & b_4 \\ \alpha(-a_5 - ab_4 + \bar{a}_5 \frac{v}{d}) & -\alpha b_4 + \bar{a}_5 \frac{v}{d} \end{bmatrix}.$$

Since  $g_2$  and  $g_5$  are submatrices of  $M \pmod{\mathfrak{P}^n}$ , they have entries in  $\mathfrak{o} + \mathfrak{P}^n$ . The following simple fact,

$$\text{If } x \in \mathfrak{o} + \mathfrak{P}^n, \text{ then } x \equiv \bar{x} \pmod{(\alpha - \bar{\alpha})\mathfrak{P}^n}, \quad (164)$$

applied to the entries of  $g_2$  resp.  $g_5$ , leads to the desired conclusion.  $\blacksquare$

### 3.2 The local pullback formula: non-archimedean case

In this subsection, we will prove the local pullback formula in the non-archimedean case. Recall the congruence subgroups defined in (17) – (20). We note that

$$\Upsilon(g \cdot \iota(k_1, k_2), s) = \Upsilon(g, s) \quad (165)$$

for any pair of elements  $k_1 \in K^{(1)}(\mathfrak{P}^n)$ ,  $k_2 \in K^H \Gamma(\mathfrak{P}^n)$ , satisfying  $\mu_1(k_1) = \mu_2(k_2)$ . This follows from the right-invariance of  $\Upsilon$  by  $C(\mathfrak{P}^n)$ . Let  $Q$  be the element

$$Q = \begin{bmatrix} 0 & 1 & & \\ 1 & 0 & & \\ & 0 & & -1 \\ & 0 & 1 & -1 \\ & 1 & 0 & \\ 1 & 1 & & 0 \end{bmatrix} \in G_3(F). \quad (166)$$

For  $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$  and  $m_2(g)$  as in (9),

$$Q \cdot \iota(g, m_2(g)) \cdot Q^{-1} = \begin{bmatrix} a & -b & b & & & \\ & 1 & & & & \\ -c & d & d & & c & c \\ & & & \mu_1(g) & & \\ & & & b & a & \end{bmatrix}, \quad (167)$$

where the matrix on the right side lies in  $P_{12}$ . It follows that if  $g \in G_1(\mathfrak{o})$ , then for any  $h \in G_3(F)$ ,

$$\Upsilon(Q \cdot \iota(g, m_2(g))h, s) = \chi(\mu_1(g)^{-1} \det(g)) \Upsilon(Qh, s). \quad (168)$$

Let  $W^{(0)}$  be the local newform for  $\tau$ , as in Corollary 1.2.4. For each  $0 \leq m \leq n$ , let the elements  $\eta_m$  be as in (34). The main object of study for the local pullback formula is the following local zeta integral,

$$Z(g, s; g_2) = q(n) \int_{\mathrm{U}(1,1)(F)} \Upsilon(Q \cdot \iota(h, g_2), s) W^{(0)}(gh) \chi^{-1}(\det(h)) dh, \quad (169)$$

where  $g \in G_1(F)$ ,  $g_2 \in \mathrm{U}(2, 2)(F)$  and  $q(n)$  is a normalizing factor equal to  $[G_1(\mathfrak{o}) : K^{(0)}(\mathfrak{P}^n)]^{-1}$ . The above integral converges absolutely for  $\mathrm{Re}(s)$  sufficiently large.

**3.2.1 Theorem. (Non-archimedean Local Pullback Formula)** *Let  $0 \leq m \leq n$ . Then, for  $\mathrm{Re}(s)$  sufficiently large,*

$$Z(g, s; \eta_m) = \begin{cases} 0 & \text{if } 0 < m \leq n, \\ T(s)W^{(0)}(g) & \text{if } m = 0, \end{cases}$$

where the factor  $T(s)$  satisfies

$$T(s)Z(s, W^\#, B) = \begin{cases} \frac{L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau})}{L(6s + 1, \chi|_{F^\times})L(6s + 2, \chi_{L/F}\chi|_{F^\times})L(6s + 3, \chi|_{F^\times})} & \text{if } n = 0, \\ L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau}) & \text{if } n > 0. \end{cases}$$

Here,  $Z(s, W^\#, B)$  is the local integral computed in Theorem 2.2.1.

The proof of Theorem 3.2.1 will require the following lemmas.

**3.2.2 Lemma.** *As a function of  $h$ , the quantity  $\Upsilon(Q \cdot \iota(h, \eta_m), s)$  depends only on the double coset  $K_1^{(1)}(\mathfrak{P}^n)hK_1^{(1)}(\mathfrak{P}^n)$ .*

**Proof.** The right invariance by  $K_1^{(1)}(\mathfrak{P}^n)$  follows easily from the right invariance of  $\Upsilon$  by  $C(\mathfrak{P}^n)$ . On the other hand, given  $k \in K_1^{(1)}(\mathfrak{P}^n)$ , we have

$$\begin{aligned} \Upsilon(Q \cdot \iota(kh, \eta_m), s) &= \Upsilon(Q \cdot \iota(kh, m_2(k)m_2(k)^{-1}\eta_m), s) \\ &= \Upsilon(Q \cdot \iota(h, m_2(k)^{-1}\eta_m), s) \\ &= \Upsilon(Q \cdot \iota(h, \eta_m\eta_m^{-1}m_2(k)^{-1}\eta_m), s) \\ &= \Upsilon(Q \cdot \iota(h, \eta_m), s) \end{aligned}$$

Note that we have used (165), (168) and the fact that  $\eta_m^{-1}m_2(k)\eta_m \in K^H\Gamma(\mathfrak{P}^n)$ . ■

Next, we note down the Cartan decompositions for  $\mathrm{U}(1, 1)(F)$ . These follow directly from the Cartan decomposition for  $\mathrm{GL}_2(F)$ . Suppose  $(\frac{L}{\mathfrak{p}}) = -1$ . Then

$$\mathrm{U}(1, 1; L)(F) = \bigsqcup_{t \geq 0} K_1^{(1)}(1)A_t K_1^{(1)}(1), \quad \text{where } A_t = \begin{bmatrix} \varpi^t & 0 \\ 0 & \varpi^{-t} \end{bmatrix}. \quad (170)$$

Suppose  $(\frac{L}{\mathfrak{p}}) = 1$ . Then

$$\mathrm{U}(1, 1; L)(F) = \bigsqcup_{t_1 \geq t_2} K_1^{(1)}(1) A_{t_1, t_2} K_1^{(1)}(1), \quad \text{where } A_{t_1, t_2} = \begin{bmatrix} \varpi_L^{t_1} \bar{\varpi}_L^{-t_2} \\ \varpi_L^{t_2} \bar{\varpi}_L^{-t_1} \end{bmatrix}. \quad (171)$$

Suppose  $(\frac{L}{\mathfrak{p}}) = 0$ . Then

$$\mathrm{U}(1, 1; L)(F) = \bigsqcup_{t \geq 0} K_1^{(1)}(1) A_t K_1^{(1)}(1), \quad \text{where } A_t = \begin{bmatrix} \varpi_L^t \\ \bar{\varpi}_L^{-t} \end{bmatrix}. \quad (172)$$

**3.2.3 Lemma.** For each  $0 \leq m \leq n$ , there exists a function  $L_m(s)$ , depending on the local data  $(F, L, \chi_0, \chi, \tau)$  but independent of  $g$ , such that, for  $\mathrm{Re}(s)$  sufficiently large,

$$Z(g, s; \eta_m) = L_m(s) W^{(0)}(g)$$

for all  $g \in G_1(F)$ .

**Proof.** We will only give the proof for the cases  $(\frac{L}{\mathfrak{p}}) = -1$  or  $0$ ; the proof for the split case  $(\frac{L}{\mathfrak{p}}) = 1$  is obtained by replacing  $A_t$  by  $A_{t_1, t_2}$  everywhere below. Recall that  $V_\tau$  is the space of Whittaker functions on  $\mathrm{GL}_2(F)$  realizing the representation  $\tau$  with respect to the character  $\psi^{-c}$ .  $W^{(0)}(g)$  is (up to a constant) the unique function in  $V_\tau$  that is right-invariant by  $K^{(1)}(\mathfrak{p}^n)$ . Observe that, by (170) resp. (172), we can write

$$q(n)^{-1} Z(g, s; \eta_m) = \sum_{t \geq 0} \int_{K_1^{(1)}(1) A_t K_1^{(1)}(1)} \Upsilon(Q \cdot \iota(h, \eta_m), s) W^{(0)}(gh) \chi^{-1}(\det h) dh. \quad (173)$$

For  $g \in G_1(F)$ , denote

$$I_t(g; s) = \int_{K_1^{(1)}(1) A_t K_1^{(1)}(1)} \Upsilon(Q \cdot \iota(h, \eta_m), s) W^{(0)}(gh) \chi^{-1}(\det h) dh. \quad (174)$$

By writing  $K_1^{(1)}(1) A_t K_1^{(1)}(1)$  as a finite disjoint union  $\bigsqcup_\gamma \gamma K_1^{(1)}(\mathfrak{P}^n)$  and using Lemma 3.2.2, we see that  $I_t$  is a finite sum of right translates of  $W^{(0)}$ . Thus,  $I_t$  lies in  $V_\tau$  for each  $t$ . In fact, we will show that  $I_t$  is a multiple of  $W^{(0)}$ . Let  $k \in K_1^{(1)}(\mathfrak{P}^n)$ . By a change of variables, and using Lemma 3.2.2, we see that

$$I_t(gk, s) = I_t(g, s). \quad (175)$$

Next, let  $l \in \mathfrak{o}^\times$  and put  $k_l = \begin{bmatrix} 1 & \\ & l \end{bmatrix}$ . Then

$$\begin{aligned} I_t(gk_l, s) &= \int_{K_1^{(1)}(1) A_t K_1^{(1)}(1)} \Upsilon(Q \cdot \iota(h, \eta_m), s) W^{(0)}(gk_l h) \chi^{-1}(\det h) dh \\ &= \int_{K_1^{(1)}(1) A_t K_1^{(1)}(1)} \Upsilon(Q \cdot \iota(k_l^{-1} h k_l, m_2(k_l)^{-1} (m_2(k_l) \eta_m m_2(k_l)^{-1}) m_2(k_l)), s) \\ &\quad \times W^{(0)}(gh) \chi^{-1}(\det h) dh \end{aligned}$$

$$= \int_{K_1^{(1)}(1)A_t K_1^{(1)}(1)} \Upsilon(Q \cdot \iota(h, \eta_m), s) W^{(0)}(gh) \chi^{-1}(\det h) dh. \quad (176)$$

In the last step above we used (168) and the fact that  $m_2(k_l)\eta_m m_2(k_l)^{-1} = \eta_m$ . The above calculations show that

$$I_t(gk_l, s) = I_t(g, s) \quad (177)$$

for all  $l \in \mathfrak{o}^\times$ . From this and (175), we conclude that  $I_t(gk, s) = I_t(g, s)$  for all  $k \in K^{(1)}(\mathfrak{P}^n)$ . The fact that the conductor of  $\tau$  equals  $\mathfrak{p}^n$  implies that, for each  $s$ , the function  $I_t(\cdot, s)$  is a multiple of  $W^{(0)}$ . Now the assertion follows immediately from (173) and (174). ■

**Proof of Theorem 3.2.1.** Let us first prove that  $Z(g, s; \eta_m) = 0$  for  $0 < m \leq n$ . We assume  $n > 0$  as otherwise the assertion is vacuous. Recall from Lemma 3.2.3 that, for each  $s$ , the function  $Z(g, s; \eta_m)$  restricted to  $\mathrm{GL}_2(F)$  lies in  $V_\tau$ . Using  $\eta_m^{-1}m_2(k)\eta_m \in K^H\Gamma(\mathfrak{P}^n)$  for  $k \in K^{(1)}(\mathfrak{p}^{n-m})$ , and a similar calculation as in (176), we get

$$Z(gk, s; \eta_m) = Z(g, s; \eta_m)$$

for any  $k \in K^{(1)}(\mathfrak{p}^{n-m}) \cap \mathrm{SL}_2(\mathfrak{o})$ . Together with (177) it follows that  $Z(g, s; \eta_m)$  is right invariant under  $K^{(1)}(\mathfrak{p}^{n-m})$ . However, because the conductor of  $\tau$  is  $n$ ,  $V_\tau$  does not contain any non-zero function that is right invariant under  $K^{(1)}(\mathfrak{p}^{n-m})$  for  $m > 0$ . This proves that  $Z(g, s; \eta_m) = 0$  whenever  $m > 0$ .

For the rest of this proof, we assume that  $m = 0$ , so  $\eta_m = \eta$ . Our task is to evaluate  $Z(g, s; \eta)$ . We first consider the case  $(\frac{L}{\mathfrak{p}}) = -1$ . For  $l \in L$ , we use  $\tilde{l}$  to denote the element  $\begin{bmatrix} l & \\ & \bar{l}^{-1} \end{bmatrix}$ . It is not hard to prove that the following decomposition holds,

$$\begin{aligned} \mathrm{U}(1, 1)(F) = & \bigsqcup_{l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})} K_1^{(1)}(\mathfrak{P}) \tilde{l} K_1^{(1)}(\mathfrak{P}) \sqcup \bigsqcup_{l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})} K_1^{(1)}(\mathfrak{P}) w \tilde{l} K_1^{(1)}(\mathfrak{P}) \\ & \sqcup \bigsqcup_{\substack{t > 0 \\ l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})}} K_1^{(1)}(\mathfrak{P}) A_t \tilde{l} K_1^{(1)}(\mathfrak{P}) \sqcup \bigsqcup_{\substack{t > 0 \\ l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})}} K_1^{(1)}(\mathfrak{P}) A_t w \tilde{l} K_1^{(1)}(\mathfrak{P}) \\ & \sqcup \bigsqcup_{\substack{t > 0 \\ l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})}} K_1^{(1)}(\mathfrak{P}) w A_t \tilde{l} K_1^{(1)}(\mathfrak{P}) \sqcup \bigsqcup_{\substack{t > 0 \\ l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})}} K_1^{(1)}(\mathfrak{P}) w A_t w \tilde{l} K_1^{(1)}(\mathfrak{P}), \end{aligned} \quad (178)$$

where  $w = \begin{bmatrix} & 1 \\ -1 & \end{bmatrix}$ . We have the following facts about the support of  $\Upsilon$ ,

$$Q \cdot \iota(W, \eta) \notin P_{12}(F)\Omega(u)C(\mathfrak{P}), \quad \text{for } W \in \{A_t w \tilde{l}, w A_t \tilde{l}, w A_t w \tilde{l} \mid t \in \mathbb{Z}_{>0}\}, u \in I_L, \quad (179)$$

$$Q \cdot \iota(w \tilde{l}, \eta) \notin P_{12}(F)\Omega(u)C(\mathfrak{P}), \quad \text{for } u \in I_L. \quad (180)$$

The statements (179) and (180) are proved by direct computations involving the relevant  $6 \times 6$  matrices; we omit the details. From the above statements, Lemma 3.2.3, and (178), we see that

$$Z(g, s; \eta) = q(n) \frac{W^{(0)}(g)}{W^{(0)}(1)} \sum_{t \geq 0} \sum_{l \in \mathfrak{o}_L^\times / (1 + \mathfrak{P})} \int_{K_1^{(1)}(\mathfrak{P}) A_t \tilde{l} K_1^{(1)}(\mathfrak{P})} \Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s) W^{(0)}(h) \chi^{-1}(\det h) dh.$$

Now, we have the non-disjoint double coset decomposition

$$\bigsqcup_{l \in \mathfrak{o}_L^\times / (1+\mathfrak{P})} K_1^{(1)}(\mathfrak{P}) A_t \tilde{l} K_1^{(1)}(\mathfrak{P}) = \bigsqcup_{k=1}^n \bigsqcup_{l \in \mathfrak{o}_L^\times / (1+\mathfrak{P}^n)} \bigcup_{\substack{y \in \mathfrak{p}/\mathfrak{p}^n \\ v(y)=k}} K_1^{(1)}(\mathfrak{P}^n) A_t \begin{bmatrix} 1 & \\ y & 1 \end{bmatrix} \tilde{l} K_1^{(1)}(\mathfrak{P}^n). \quad (181)$$

Again, by explicit calculation, one verifies that  $Q \cdot \iota(A_t \begin{bmatrix} 1 & \\ y & 1 \end{bmatrix} \tilde{l}, \eta)$  does not belong to any of the sets  $P_{12}(F)\Omega_r C(\mathfrak{P}^n)$  if  $v(y) < n$ . It follows that

$$\begin{aligned} Z(g, s; \eta) &= q(n) \frac{W^{(0)}(g)}{W^{(0)}(1)} \sum_{t \geq 0} \sum_{l \in \mathfrak{o}_L^\times / (1+\mathfrak{P}^n)} \Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s) \int_{K_1^{(1)}(\mathfrak{P}^n) A_t \tilde{l} K_1^{(1)}(\mathfrak{P}^n)} W^{(0)}(h) \chi^{-1}(\det h) dh \\ &= q(n) \frac{W^{(0)}(g)}{W^{(0)}(1)} \sum_{t \geq 0} \sum_{l \in \mathfrak{o}_L^\times / (1+\mathfrak{P}^n)} \Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s) \chi(l^{-1}) \int_{K_1^{(1)}(\mathfrak{P}^n) A_t K_1^{(1)}(\mathfrak{P}^n)} W^{(0)}(h) dh \\ &= T(s) W^{(0)}(g), \end{aligned}$$

where

$$T(s) = \frac{q(n)}{W^{(0)}(1)} \sum_{t \geq 0} \sum_{l \in \mathfrak{o}_L^\times / (1+\mathfrak{P}^n)} \Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s) \chi(l^{-1}) \int_{K_1^{(1)}(\mathfrak{P}^n) A_t K_1^{(1)}(\mathfrak{P}^n)} W^{(0)}(h) dh. \quad (182)$$

To evaluate  $T(s)$ , we note from the theory of Hecke operators on  $\mathrm{GL}_2(F)$  that

$$\int_{K_1^{(1)}(\mathfrak{P}^n) A_t K_1^{(1)}(\mathfrak{P}^n)} \tau(h) W^{(0)}(h) dh = \mathrm{vol}(K_1^{(1)}(\mathfrak{P}^n)) \lambda_t W^{(0)}, \quad (183)$$

where  $\lambda_t$  depends on  $t$  and  $\tau$ . Using familiar double coset decompositions, the eigenvalues  $\lambda_t$  can easily be calculated. The result is as follows.

- If  $\tau = \beta_1 \times \beta_2$  with unramified characters  $\beta_1, \beta_2$ , then  $\lambda_t = \gamma_t - \gamma_{t-1}$  where
$$\gamma_t = q^t \omega_\tau(\varpi)^{-t} \frac{\beta_1(\varpi)^{2t+1} - \beta_2(\varpi)^{2t+1}}{\beta_1(\varpi) - \beta_2(\varpi)}$$
for  $t \geq 0$ , and  $\gamma_t = 0$  for  $t < 0$  (for  $\beta_1 = \beta_2$ , the fraction is to be interpreted as  $(2t+1)\beta_1(\varpi)^{2t}$ ).
- If  $\tau$  is an unramified twist of the Steinberg representation, then  $\lambda_t = 1$  for all  $t \geq 0$ .
- If  $\tau = \beta_1 \times \beta_2$  is a principal series representation with an unramified character  $\beta_1$  and a ramified character  $\beta_2$ , then  $\lambda_t = q^t \beta_1(\varpi)^{-t} \beta_2(\varpi)^t$  for all  $t \geq 0$ .
- If  $\tau$  is supercuspidal, or a ramified twist of the Steinberg representation, or an irreducible principal series representation induced from two ramified characters  $\beta_1, \beta_2$ , then  $\lambda_0 = 1$  and  $\lambda_t = 0$  for  $t > 0$ .

We substitute the above formulas for  $\lambda_t$  in the integral inside (182). Then, we use the definition of  $\Upsilon$  to compute the term  $\Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s)$ ; it turns out that

$$\Upsilon(Q \cdot \iota(A_t \tilde{l}, \eta), s) = q^{-6t(s+\frac{1}{2})} \chi(l) \chi(\varpi^t). \quad (184)$$

After making these substitutions, it is easy to evaluate  $T(s)$  for the possible types of  $\tau$  listed above simply by summing the geometric series. This proves Theorem 3.2.1 in the inert case. The proofs for the cases  $(\frac{L}{\mathfrak{p}}) = 0$  or 1 are very similar to the above. The details are left to the reader. ■

### 3.3 Local sections: archimedean case

In this subsection,  $F = \mathbb{R}$  and  $L = \mathbb{C}$ . Let  $\tau$  be as in Sect. 1.3, and let  $l_1$  be any of the weights occurring in  $\tau$ . Let  $\chi_0$  be the character of  $\mathbb{C}^\times$  such that  $\chi_0|_{\mathbb{R}^\times} = \omega_\tau$  and  $\chi_0(\zeta) = \zeta^{-l_1}$  for  $\zeta \in \mathbb{C}^\times$ ,  $|\zeta| = 1$ . Let  $\chi$  be the character of  $\mathbb{C}^\times$  given by  $\chi(\zeta) = \chi_0(\bar{\zeta})^{-1}$ .

We define  $I(\tilde{\chi}, s)$  in the present (archimedean) case in exactly the same manner as it was defined in the non-archimedean case (see (161), (162)). In this subsection, we will construct a special element of  $I(\tilde{\chi}, s)$ . Let  $\eta_0$  be the matrix defined in (63). For  $\theta \in \mathbb{R}$ , let

$$r(\theta) = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \in \mathrm{SO}(2),$$

and

$$r_{\times}(\theta) = \begin{bmatrix} \cos(\theta) & & & \sin(\theta) \\ & 1 & & 0 \\ & & \cos(\theta) & \sin(\theta) \\ & & -\sin(\theta) & \cos(\theta) \\ 0 & & & 1 \\ -\sin(\theta) & & & \cos(\theta) \end{bmatrix} \in K_\infty^{G_3}, \quad (185)$$

where  $K_\infty^{G_3}$  is the maximal compact subgroup of  $G_3^+(\mathbb{R}) = \{g \in G_3(\mathbb{R}) \mid \mu_3(g) > 0\}$ . Explicitly,

$$K_\infty^{G_3} = \left\{ \begin{bmatrix} A & B \\ -B & A \end{bmatrix} \mid A, B \in \mathrm{Mat}_{3,3}(\mathbb{C}), {}^t \bar{A}B = {}^t \bar{B}A, {}^t \bar{A}A + {}^t \bar{B}B = 1 \right\}.$$

Also, we let

$$w_Q = \begin{bmatrix} 1 & & & 1 \\ & 1 & & -1 \\ & & 1 & \\ & & & 1 \end{bmatrix}, \quad s_1 = \begin{bmatrix} 1 & & & & 1 \\ & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix}, \quad (186)$$

and

$$t_\infty = w_Q \cdot \iota(1, \eta_0) = \iota(r(\pi/2), s_1 \eta_0). \quad (187)$$

Let  $l$  be a positive integer (in our application we will consider a discrete series representation of  $\mathrm{PGSp}_4(\mathbb{R})$  with scalar minimal  $K$ -type  $(l, l)$ ). To ease notation, we will denote the function  $\Phi_{|l-l_1|, l, -l_1, l_1}^\#$  defined in (62) by  $J_\infty$ . Explicitly,

$$J_\infty = \begin{cases} i^{l-l_1} \hat{b}^{l_1-l} (\hat{a}\hat{d} - \hat{b}\hat{c})^{l-l_1} D^{-l} & \text{if } l \leq l_1, \\ i^{l_1-l} \hat{c}^{l-l_1} D^{-l} & \text{if } l \geq l_1, \end{cases} \quad (188)$$

where  $D(g) = \det(J(g, i_2))$ , and the functions  $\hat{a}, \hat{b}, \hat{c}, \hat{d}$  are defined before Lemma 1.3.3. Note that  $J_\infty(\eta_0) = 1$ .

By the Iwasawa decomposition,  $G_3(\mathbb{R}) = P_{12}(\mathbb{R}) K_\infty^{G_3}$ . The following lemma provides a criterion for when functions on  $K_\infty^{G_3}$  can be extended to nice sections in  $I(\tilde{\chi}, s)$ .

**3.3.1 Lemma.** *Suppose  $\Upsilon_\infty$  is an analytic function on  $K_\infty^{G_3}$  that satisfies the following conditions.*

i) For all  $A \in \mathrm{U}(3)$  and all  $g \in K_\infty^{G_3}$ ,

$$\Upsilon_\infty\left(\begin{bmatrix} A & \\ & A \end{bmatrix} g\right) = \det(A)^{-l_1} \Upsilon_\infty(g). \quad (189)$$

ii) For all  $\theta \in \mathbb{R}$  and all  $k \in K_\infty^{G_2}$ ,

$$\Upsilon_\infty(r_\times(\theta) t_\infty \iota(1, k)) = \Upsilon_\infty(r_\times(\theta) t_\infty) J_\infty(\eta_0 k). \quad (190)$$

iii) For all  $\varphi \in \mathbb{R}$  and all  $g \in K_\infty^{G_3}$ ,

$$\Upsilon_\infty(g \iota(r(\varphi), 1)) = e^{-il_1\varphi} \Upsilon_\infty(g). \quad (191)$$

Then  $\Upsilon_\infty$  can be extended in a unique way to an analytic function on  $G_3(\mathbb{R})$  satisfying the following conditions.

i)

$$\Upsilon_\infty \in I(\tilde{\chi}, s). \quad (192)$$

ii) For all  $\zeta \in S^1$  and all  $h \in \mathrm{U}(1, 1)(\mathbb{R})$

$$\Upsilon_\infty(Q \cdot \iota(\begin{bmatrix} \zeta & \\ & \zeta \end{bmatrix} h, \eta_0), s) = \zeta^{-l_1} \Upsilon_\infty(Q \cdot \iota(h, \eta_0), s). \quad (193)$$

iii) We have the following equation for any  $k \in K_\infty^{G_2}$  and  $h \in \mathrm{U}(1, 1)(\mathbb{R})$ :

$$\Upsilon_\infty(Q \cdot \iota(h, \eta_0 k), s) = \Upsilon_\infty(Q \cdot \iota(h, \eta_0), s) J_\infty(\eta_0 k). \quad (194)$$

iv) For all  $\varphi \in \mathbb{R}$  and all  $g \in G_3(\mathbb{R})$ ,

$$\Upsilon_\infty(g \iota(r(\varphi), 1), s) = e^{-il_1\varphi} \Upsilon_\infty(g, s). \quad (195)$$

v) For all  $\varphi \in \mathbb{R}$  and all  $h \in \mathrm{U}(1, 1)(\mathbb{R})$ ,

$$\Upsilon_\infty(Q \cdot \iota(r(\varphi)h, \eta_0), s) = e^{-il_1\varphi} \Upsilon_\infty(Q \cdot \iota(h, \eta_0), s). \quad (196)$$

**Proof.** Using the Iwasawa decomposition, it is easy to see that  $\Upsilon_\infty$  can be extended in a unique way to an analytic function on  $G_3(\mathbb{R})$  satisfying condition (192). Note that condition (189) is tailored so that the extension is well-defined. Next, another appeal to the Iwasawa decomposition and the fact that  $\Upsilon_\infty \in I(\tilde{\chi}, s)$  shows that (191) implies (195). We now prove (194). We have the identity

$$Q \cdot \iota\left(\begin{bmatrix} \sqrt{a} & \\ & \sqrt{a}^{-1} \end{bmatrix}, 1\right) = p_a k_a w_Q \quad (197)$$

with

$$p_a = \begin{bmatrix} 1 & & & \frac{1}{1+a} \\ & 1 & & \\ & & 1 & \frac{1}{1+a} \\ & & & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\frac{a}{1+a}} & & & \\ & 1 & & \\ & & \sqrt{\frac{1}{1+a}} & \\ & & & \sqrt{\frac{1+a}{a}} \end{bmatrix} \in P_{12}(\mathbb{R}) \quad (198)$$

and

$$k_a = \begin{bmatrix} \sqrt{\frac{a}{1+a}} & & & & \frac{-1}{\sqrt{1+a}} \\ & 1 & & & 0 \\ & & \sqrt{\frac{a}{1+a}} & \frac{-1}{\sqrt{1+a}} & \\ & & \frac{1}{\sqrt{1+a}} & \sqrt{\frac{a}{1+a}} & \\ 0 & & & & 1 \\ \frac{1}{\sqrt{1+a}} & & & & \sqrt{\frac{a}{1+a}} \end{bmatrix} \in K_\infty^{G_3}. \quad (199)$$

On the other hand, observe that  $k_a = r_\times(\theta)$  for  $\theta$  ranging in an open subset of  $\mathbb{R}/2\pi\mathbb{Z}$ ; so condition (190) is equivalent to

$$\Upsilon_\infty(k_a w_Q \cdot \iota(1, \eta_0 k), s) = \Upsilon_\infty(k_a w_Q \cdot \iota(1, \eta_0), s) J_\infty(\eta_0 k). \quad (200)$$

Using (167) and (197), properties of  $J_\infty$  imply that condition (194) holds for all  $h$  of the form  $r(\varphi) \begin{bmatrix} \sqrt{a} & \\ & \sqrt{a}-1 \end{bmatrix}$ . A similar calculation shows that (194) holds for all elements  $h$  of the form  $\begin{bmatrix} \zeta & \\ \zeta & \end{bmatrix} r(\varphi) \begin{bmatrix} \sqrt{a} & \\ & \sqrt{a}-1 \end{bmatrix}$ . In combination with (195) it follows that (194) holds for all  $h \in \mathrm{U}(1, 1)(\mathbb{R})$ . Finally, (193) and (196) can be verified using (168), (194), and the properties of  $J_\infty$ . ■

We define the functions  $x_{ij}$  on  $K_\infty^{G_3}$  by

$$x_{ij}(g) = ij\text{-coefficient of } J({}^t \bar{g} \tilde{g}, I), \quad g \in K_\infty^{G_3}, \quad (201)$$

where

$$\tilde{g} = \begin{bmatrix} A & -B \\ B & A \end{bmatrix} \text{ for } g = \begin{bmatrix} A & B \\ -B & A \end{bmatrix}.$$

Any polynomial expression in the functions  $x_{ij}$  and their complex conjugates is  $K_\infty^{G_3}$ -finite. We further define

$$\begin{aligned} X_1 &:= ((1 - |x_{33}|^2)x_{11} + x_{13}x_{31}\overline{x_{33}})\overline{x_{13}} + ((1 - |x_{33}|^2)x_{12} + x_{13}x_{32}\overline{x_{33}})\overline{x_{23}}, \\ X_2 &:= ((1 - |x_{33}|^2)x_{21} + x_{23}x_{31}\overline{x_{33}})\overline{x_{13}} + ((1 - |x_{33}|^2)x_{22} + x_{23}x_{32}\overline{x_{33}})\overline{x_{23}}, \\ Y_1 &:= ((1 - |x_{33}|^2)\overline{x_{11}} + \overline{x_{13}x_{31}}x_{33})x_{31} + ((1 - |x_{33}|^2)\overline{x_{21}} + \overline{x_{23}x_{31}}x_{33})x_{32}, \\ Y_2 &:= ((1 - |x_{33}|^2)\overline{x_{12}} + \overline{x_{13}x_{32}}x_{33})x_{31} + ((1 - |x_{33}|^2)\overline{x_{22}} + \overline{x_{23}x_{32}}x_{33})x_{32}. \end{aligned}$$

Let  $\Upsilon_0$  be the function on  $K_\infty^{G_3}$  given by

$$\Upsilon_0 = \begin{cases} (\overline{x_{31}}Y_2 - \overline{x_{32}}Y_1)^{l_1-l} & \text{if } l \leq l_1, \\ (x_{13}X_2 - x_{23}X_1)^{l-l_1} & \text{if } l \geq l_1. \end{cases} \quad (202)$$

By explicit calculation, one verifies that

$$\Upsilon_0(r_\times(\theta) \iota(1, s_1 \eta_0)) = (-1)^{l_1-l} \sin(2\theta)^{4|l-l_1|}. \quad (203)$$

**3.3.2 Lemma.** *Let  $\Upsilon_0$  be as in (202). Then the function  $\Upsilon_\infty(g) := \Upsilon_0(g) \det(J(g, i_2))^{-l_1}$  is  $K_\infty^{G_3}$ -finite and satisfies the conditions from Lemma 3.3.1. Moreover,*

$$\Upsilon_\infty(r_\times(\theta) t_\infty) = (-i)^{l_1} (-1)^l \sin(2\theta)^{4|l-l_1|} \quad (204)$$

for all  $\theta \in \mathbb{R}$ . If  $\Upsilon_\infty(\cdot, s)$  denotes the extension of  $\Upsilon_\infty$  to a function on all of  $G_3(\mathbb{R})$ , then

$$\Upsilon_\infty(Q \iota(\begin{bmatrix} \sqrt{a} & \\ & \sqrt{a}^{-1} \end{bmatrix}, \eta_0), s) = 2^{4|l-l_1|} (-i)^{l_1} (-1)^l (\sqrt{a} + \sqrt{a}^{-1})^{q-6(s+\frac{1}{2})-4|l-l_1|} \quad (205)$$

for all  $a > 0$ . Here,  $q \in \mathbb{C}$  is such that  $\omega_\tau(a) = a^q$  for  $a > 0$ .

**Proof.** From the construction, it is a routine calculation to verify that  $\Upsilon_\infty$  satisfies the conditions (189) and (190). Property (191) follows from the right transformation properties of the functions  $x_{ij}$ . Property (204) follows easily from (203). To prove (205), note that, by (197),

$$Q \iota(\begin{bmatrix} \sqrt{a} & \\ & \sqrt{a}^{-1} \end{bmatrix}, 1) = p_{ar\times}(\theta) \iota(\begin{bmatrix} 1 \\ -1 \end{bmatrix}, s_1) = p_{ar\times}(\theta) t_\infty \iota(1, \eta_0^{-1})$$

with  $p_a$  as in (198) and  $\theta \in \mathbb{R}$  such that  $\cos(\theta) = \sqrt{\frac{a}{1+a}}$  and  $\sin(\theta) = \frac{-1}{\sqrt{1+a}}$ . This leads to the claimed result in a straightforward manner. ■

### 3.4 The local pullback formula: archimedean case

In this section, we will prove the local pullback formula in the archimedean case. Let  $\Upsilon_\infty(\cdot, s)$  be the element of  $I(\tilde{\chi}, s)$  constructed in Lemma 3.3.2. For any  $g_2 \in U(2, 2)(F)$ ,  $g \in G_1(F)$  and  $s \in \mathbb{C}$  let

$$Z_\infty(g, s; g_2) = \int_{U(1,1)(\mathbb{R})} \Upsilon_\infty(Q \cdot \iota(h, g_2), s) W_{l_1}(gh) \chi(\det(h))^{-1} dh, \quad (206)$$

which converges absolutely for  $\operatorname{Re}(s)$  sufficiently large. Here,  $W_{l_1}$  is as in (65). For simplicity, we will assume that  $\mathbf{c} = 1$ .

**3.4.1 Theorem. (Archimedean Local Pullback Formula)** *Let  $l$  be a positive integer, and let  $l_1$  be any of the weights occurring in  $\tau$ . Then, for  $\operatorname{Re}(s)$  sufficiently large,*

$$Z_\infty(g, s; \eta_0) = T_\infty(s) W_{l_1}(g), \quad (207)$$

where, up to a non-zero constant (depending on  $\tau_\infty$  and  $l$  and  $l_1$ , but not on  $s$ ),

$$T_\infty(s) = 2^{-6s} \frac{\Gamma(3s + 1 - \frac{q}{2} + 2|l_1 - l| - \frac{p}{2}) \Gamma(3s + 1 - \frac{q}{2} + 2|l_1 - l| + \frac{p}{2})}{\Gamma(3s + \frac{3}{2} - \frac{q}{2} + 2|l_1 - l| - \frac{l_1}{2}) \Gamma(3s + \frac{3}{2} - \frac{q}{2} + 2|l_1 - l| + \frac{l_1}{2})}.$$

Here,  $p$  and  $q$  are as in (46).

**Proof.** Recall that we have chosen  $t^+ \in \mathbb{R}_{>0}$  and normalized the function  $W_{l_1}$  such that  $W_{l_1}(\begin{bmatrix} t^+ & \\ & 1 \end{bmatrix}) = 1$ ; see (66). By changing the value of  $p$  slightly and using the holomorphy of both sides of (207) in  $p$ , we may work under the additional assumption that  $W_{l_1}(1) \neq 0$ . We have

$$\begin{aligned} Z_\infty(g, s; \eta_0) &= \int_{U(1,1)(\mathbb{R})} \Upsilon_\infty(Q \cdot \iota(h, \eta_0), s) W_{l_1}(gh) \chi^{-1}(\det(h)) dh \\ &\stackrel{(193)}{=} \int_{U(1,1)(\mathbb{R})/Z} \Upsilon_\infty(Q \cdot \iota(h, \eta_0), s) W_{l_1}(gh) \chi^{-1}(\det(h)) dh \end{aligned}$$

$$= \int_{\mathrm{SL}(2, \mathbb{R})} F_1(h) W_{l_1}(gh) dh,$$

where the function  $F_1$  on  $\mathrm{SL}_2(\mathbb{R})$  is defined by  $F_1(h) := \Upsilon_\infty(Q \iota(h, \eta_0), s)$ . Hence  $Z_\infty(g, s; \eta_0)$  is in the space of  $\tau$ . It follows from (196) that  $Z_\infty(g, s; \eta_0)$  is a vector of weight  $l_1$ . By irreducibility, there is (up to multiples) only one vector of weight  $l_1$  in the space of  $\tau$ , namely  $W_{l_1}$ . It follows that  $Z_\infty(g, s; \eta_0)$  is a multiple of  $W_{l_1}(g)$ . By an easy calculation, in terms of the Iwasawa decomposition,

$$F_1\left(\begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{a} & \\ \sqrt{a}^{-1} & \end{bmatrix} r(\theta)\right) = (-i)^{l_1} e^{-il_1\theta} \left(\frac{(1+a)^2 + b^2}{a}\right)^{\frac{q}{2}-3(s+\frac{1}{2})-2|l_1-l|} \left(\frac{b-i(a+1)}{|b-i(a+1)|}\right)^{-l_1}.$$

So we get that  $Z_\infty(g, s; \eta_0) = T_\infty(s) W_{l_1}(g)$ , where

$$\begin{aligned} T_\infty(s) W_{l_1}(1) &= Z_\infty(1, s; \eta_0) \\ &= (-i)^{l_1} \int_{-\infty}^{\infty} \int_0^{\infty} a^{-1} \left(\frac{(1+a)^2 + b^2}{a}\right)^{\frac{q}{2}-3(s+\frac{1}{2})-2|l_1-l|} \left(\frac{b-i(a+1)}{|b-i(a+1)|}\right)^{-l_1} \\ &\quad e^{2\pi i b} W_{l_1}\left(\begin{bmatrix} \sqrt{a} & \\ \sqrt{a}^{-1} & \end{bmatrix}\right) d^\times a db. \end{aligned}$$

For brevity, we make the following substitutions,

$$\begin{aligned} s' &= \frac{q}{2} - 3(s + \frac{1}{2}) - 2|l_1 - l|, \\ s_1 &= -s' - \frac{l_1}{2}, \quad s_2 = -s' - \frac{1}{2} - \frac{p}{2}, \quad s_3 = -s' - \frac{1}{2} + \frac{p}{2}, \quad s_4 = -s' + \frac{l_1}{2}. \end{aligned}$$

By the integral formula from [24, (6.11)]), the first formula in Sect. 7.5.2 of [39], and Lemma 3.4.2 below,

$$\begin{aligned} Z_\infty(1, s; \eta_0) &= \frac{(2\pi)^{-2s'}}{\Gamma(s_1)\Gamma(s_4)} \int_0^\infty \int_0^\infty a^{-s'-1} t^{s_1-1} (t+1)^{s_4-1} e^{-2\pi(a+1)(1+2t)} W_{l_1}\left(\begin{bmatrix} \sqrt{a} & \\ \sqrt{a}^{-1} & \end{bmatrix}\right) d^\times a dt \\ &= a^+ 2^{q+2} \pi^{-s'+1+\frac{q}{2}} \frac{\Gamma(s_2)\Gamma(s_3)}{\Gamma(s_1)^2\Gamma(s_4)} \int_0^\infty t^{s_1-1} (t+1)^{s_4-1} e^{-2\pi(1+2t)} {}_2F_1(s_2, s_3, s_1; -t) dt \\ &= a^+ 2^{q+1-p-2s_2} \pi^{1+\frac{q}{2}} \frac{\Gamma(s_2)\Gamma(s_3)}{\Gamma(s_1)\Gamma(s_4)} W_{\frac{l_1}{2}, \frac{p}{2}}(4\pi) \\ &= 4^{s'+1} \pi \frac{\Gamma(s_2)\Gamma(s_3)}{\Gamma(s_1)\Gamma(s_4)} W_{l_1}(1), \end{aligned}$$

and so

$$T_\infty(s) = 4^{s'+1} \pi \frac{\Gamma(s_2)\Gamma(s_3)}{\Gamma(s_1)\Gamma(s_4)}.$$

This concludes the proof. ■

**3.4.2 Lemma.** *For complex numbers  $s_1, s_2, s_3$  with  $\mathrm{Re}(s_1) > 0$ ,*

$$\int_0^\infty t^{s_1-1} (t+1)^{s_2+s_3-s_1} e^{-4\pi t} {}_2F_1(s_2, s_3, s_1; -t) dt = \Gamma(s_1) (4\pi)^{-\frac{s_2+s_3+1}{2}} e^{2\pi} W_{\frac{s_2+s_3+1}{2}-s_1, \frac{s_3-s_2}{2}}(4\pi).$$

**Proof.** This follows by first applying the third equation of [21, (9.131, 1)], followed by the integral formula [21, (7.522, 1)].  $\blacksquare$

### 3.5 The global pullback formula

In the following we use the global set-up of Theorem 2.3.2. We set the number  $l_2$  to be  $-l_1$ . We will hence work with the section  $f = f_{|l_1-l|, l, -l_1, l_1}$  in  $I_{\mathbb{C}}(s, \chi, \chi_0, \tau)$ . It gives rise to the Eisenstein series  $E(g, s; f)$  via (130). In this section we will prove the global pullback formula, which expresses the Eisenstein series  $E(g, s; f)$  on  $G_2(\mathbb{A})$  in terms of the pullback of a simpler Eisenstein series on  $G_3(\mathbb{A})$ .

Let  $\tilde{\chi}$  be the character on  $P_{12}(\mathbb{A})$  defined by  $\tilde{\chi}(m(A, v)n) = \chi(v^{-1} \det(A))$ ; see (160) for the corresponding local definition. For  $s \in \mathbb{C}$ , we form the global induced representation

$$I(\tilde{\chi}, s) = \text{Ind}_{P_{12}(\mathbb{A})}^{G_3(\mathbb{A})}(\tilde{\chi}\delta_{12}^s) \quad (208)$$

(see (15)), consisting of functions  $\Upsilon$  on  $G_3(\mathbb{A})$  such that

$$\Upsilon(m(A, v)ng, s) = |v|^{-9(s+\frac{1}{2})} |N(\det A)|^{3(s+\frac{1}{2})} \chi(v^{-1} \det(A)) \Upsilon(g, s) \quad (209)$$

for  $n \in N_{12}(\mathbb{A})$ ,  $m(A, v) \in M_{12}(\mathbb{A})$ ,  $g \in G_3(\mathbb{A})$ . Now, let  $\Upsilon = \otimes_v \Upsilon_v \in I(\tilde{\chi}, s)$ , where  $\Upsilon_v$  is defined by (163) in the non-archimedean case and defined as in Lemma 3.3.2 in the archimedean case. We define the Eisenstein series  $E_{\Upsilon}(g, s)$  on  $G_3(\mathbb{A})$  by

$$E_{\Upsilon}(g, s) = \sum_{\gamma \in P_{12}(\mathbb{Q}) \backslash G_3(\mathbb{Q})} \Upsilon(\gamma g, s) \quad (210)$$

for  $\text{Re}(s)$  sufficiently large, and by analytic continuation elsewhere. Furthermore, let

$$T(s) = \prod_v T_v(s), \quad (211)$$

where the local functions  $T_v(s)$  are defined by Theorem 3.2.1 in the non-archimedean case and by Theorem 3.4.1 in the archimedean case. Note that though (211) makes sense for  $\text{Re}(s)$  sufficiently large; it is clear from the definitions of  $T_v(s)$  that  $T(s)$  can be analytically continued to a meromorphic function on the entire complex plane (it is effectively just a ratio of global  $L$ -functions).

**3.5.1 Theorem. (Global Pullback Formula)** Let  $\Psi$  be the cusp form in the space of  $\tau$  corresponding to a local newform at all non-archimedean places, a vector of weight  $l_1$  at the archimedean place, and with the same normalization for the corresponding Whittaker function  $W_{\Psi}$  as in (140). Let  $\Psi$  be extended to a function on  $G_1(\mathbb{A})$  via  $\Psi(ag) = \chi_0(a)\Psi(g)$  for  $a \in \mathbb{A}_L^{\times}$ ,  $g \in \text{GL}_2(\mathbb{A})$ . For an element  $g \in G_2(\mathbb{A})$ , let  $\text{U}[g](\mathbb{A})$  denote the subset of  $G_1(\mathbb{A})$  consisting of all elements  $h$  such that  $\mu_2(g) = \mu_1(h)$ . Then we have the following identity of meromorphic functions,

$$\chi(\mu_2(g)) \int_{\text{U}(1,1)(\mathbb{Q}) \backslash \text{U}[g](\mathbb{A})} E_{\Upsilon}(\iota(h, g), s) \Psi(h) \chi(\det(h))^{-1} dh = T(s) E(g, s; f), \quad (212)$$

where  $f = f_{|l_1-l|, l, -l_1, l_1}$  as in Theorem 2.3.2.

**Proof.** Let  $\mathcal{E}(g, s)$  denote the left hand side above. Note that  $E_\Upsilon(\iota(g, h), s)$  is slowly increasing away from its poles, while  $\Psi(h)$  is rapidly decreasing. Thus  $\mathcal{E}(g, s)$  converges uniformly and absolutely for  $s \in \mathbb{C}$  away from the poles of the Eisenstein series  $E_\Upsilon$ . Hence, it is enough to prove the theorem for  $\operatorname{Re}(s)$  sufficiently large. Since  $E_\Upsilon$  is left invariant by  $G_3(\mathbb{Q})$ ,

$$\mathcal{E}(g, s) = \chi(\mu_2(g)) \int_{\operatorname{U}(1,1)(\mathbb{Q}) \backslash \operatorname{U}[g](\mathbb{A})} E_\Upsilon(Q \cdot \iota(h, g), s) \Psi(h) \chi(\det(h))^{-1} dh. \quad (213)$$

Let  $V(\mathbb{Q})$  denote the subgroup of  $G_3(\mathbb{Q})$  defined by

$$V(\mathbb{Q}) = \{Q \iota(g_1, g_2) Q^{-1} \mid g_i \in G_i(\mathbb{Q}), \mu_1(g_1) = \mu_2(g_2)\}.$$

Recall from [57, Prop. 2.4] that  $|P_{12}(\mathbb{Q}) \backslash G_3(\mathbb{Q}) / V(\mathbb{Q})| = 2$ . We take the identity element as one of the double coset representatives, and denote the other one by  $v$ . Thus

$$G_3(\mathbb{Q}) = P_{12}(\mathbb{Q})V(\mathbb{Q}) \sqcup P_{12}(\mathbb{Q})vV(\mathbb{Q}).$$

Let  $R_1 \subset V(\mathbb{Q})$  and  $R_2 \subset vV(\mathbb{Q})$  be corresponding sets of coset representatives, such that

$$P_{12}(\mathbb{Q})V(\mathbb{Q}) = \bigsqcup_{s \in R_1} P_{12}(\mathbb{Q})s, \quad P_{12}(\mathbb{Q})vV(\mathbb{Q}) = \bigsqcup_{s \in R_2} P_{12}(\mathbb{Q})s.$$

For the Eisenstein series defined in (210), we can write  $E_\Upsilon(h, s) = E_\Upsilon^1(h, s) + E_\Upsilon^2(h, s)$ , where

$$E_\Upsilon^1(h, s) = \sum_{\gamma \in R_1} \Upsilon(\gamma h, s), \quad E_\Upsilon^2(h, s) = \sum_{\gamma \in R_2} \Upsilon(\gamma h, s).$$

Now, by [57, 22.9] the orbit of  $v$  is ‘negligible’ for our integral, that is,

$$\int_{\operatorname{U}(1,1)(\mathbb{Q}) \backslash \operatorname{U}[g](\mathbb{A})} E_\Upsilon^2(Q \cdot \iota(h, g), s) \Psi(h) \chi(\det(h))^{-1} dh = 0$$

for all  $g \in G_2(\mathbb{A})$ . It follows that

$$\mathcal{E}(g, s) = \chi(\mu_2(g)) \int_{\operatorname{U}(1,1)(\mathbb{Q}) \backslash \operatorname{U}[g](\mathbb{A})} E_\Upsilon^1(Q \cdot \iota(h, g), s) \Psi(h) \chi(\det(h))^{-1} dh. \quad (214)$$

On the other hand, by [57, Prop. 2.7], we can take  $R_1$  to be the following set,

$$R_1 = \{Q \iota(1, m_2(\xi)\beta) Q^{-1} \mid \xi \in \operatorname{U}(1, 1)(\mathbb{Q}), \beta \in P(\mathbb{Q}) \backslash G_2(\mathbb{Q})\}, \quad (215)$$

where  $m_2(\xi)$  is as in (9), and where the  $\beta$  are chosen to have  $\mu_2(\beta) = 1$ . For  $\operatorname{Re}(s)$  large, we therefore have

$$E_\Upsilon^1(Q \cdot \iota(h, g), s) = \sum_{\substack{\xi \in \operatorname{U}(1,1)(\mathbb{Q}) \\ \beta \in P(\mathbb{Q}) \backslash G_2(\mathbb{Q})}} \Upsilon(Q \cdot \iota(h, m_2(\xi)\beta g), s).$$

Substituting into (214) and using that  $Q \iota(\xi, m_2(\xi)) Q^{-1} \in P_{12}(\mathbb{Q})$  by (167), we have

$$\mathcal{E}(g, s) = \chi(\mu_2(g)) \int_{\operatorname{U}(1,1)(\mathbb{Q}) \backslash \operatorname{U}[g](\mathbb{A})} \sum_{\substack{\xi \in \operatorname{U}(1,1)(\mathbb{Q}) \\ \beta \in P(\mathbb{Q}) \backslash G_2(\mathbb{Q})}} \Upsilon(Q \cdot \iota(h, m_2(\xi)\beta g), s) \Psi(h) \chi(\det(h))^{-1} dh$$

$$= \sum_{\beta \in P(\mathbb{Q}) \setminus G_2(\mathbb{Q})} \chi(\mu_2(g)) \int_{U[g](\mathbb{A})} \Upsilon(Q \cdot \iota(h, \beta g), s) \Psi(h) \chi(\det(h))^{-1} dh.$$

Let

$$\Upsilon_\Psi(g, s) = \chi(\mu_2(g)) \int_{U[g](\mathbb{A})} \Upsilon(Q \cdot \iota(h, g), s) \Psi(h) \chi(\det(h))^{-1} dh. \quad (216)$$

If we can show that, for each  $g \in G_2(\mathbb{Q})$ ,

$$\Upsilon_\Psi(g, s) = T(s)f(g, s), \quad (217)$$

the proof will be complete. By [57], we know that the integral above converges absolutely and uniformly on compact sets for  $\operatorname{Re}(s)$  large. We are going to evaluate the above integral for such  $s$ . For a finite place  $p$  such that  $\tau_p$  has conductor  $\mathfrak{p}^n$ , note that

$$G_2(\mathbb{Q}_p) = \bigsqcup_{m=0}^n P(\mathbb{Q}_p) \eta_m K^H \Gamma(\mathfrak{P}^n)$$

by Proposition 1.2.1. For  $k \in K^H \Gamma(\mathfrak{P}^n)$ , we may write  $k = m_2 \begin{pmatrix} 1 & 0 \\ 0 & \lambda \end{pmatrix} k'$ , where  $\lambda = \mu_2(k)$  and  $\mu_2(k') = 1$ . Using the fact that both sides of (217) are invariant under the right action on  $g$  by elements  $k_p \in K^H \Gamma(\mathfrak{P}^n)$  satisfying  $\mu_2(k_p) = 1$ , and the above observations, it follows that in order to prove our theorem, it is enough to prove (217) for  $g \in G_2(\mathbb{A})$  of the form

$$g = m_1(a)m_2(b)n\kappa k_\infty,$$

where  $m_i \in M^{(i)}(\mathbb{A})$ ,  $n \in N(\mathbb{A})$ ,  $k_\infty \in K_\infty^{G_2}$ , and  $\kappa = (\kappa_v)_v \in \prod_v K_v^{G_2}$  satisfies

- $\kappa_v \in \{\eta_0, \dots, \eta_n\}$  if  $v = p$  and  $\tau_p$  has conductor  $p^n$ ,  $n > 0$ ,
- $\kappa_v = \eta_0$  if  $v = \infty$ ,
- $\kappa_v = 1$  otherwise.

For such  $g$ , we calculate

$$\begin{aligned} \Upsilon_\Psi(g, s) &= \chi(\mu_1(b)) \int_{U[m_2(b)](\mathbb{A})} \Upsilon(Q \cdot \iota(h, m_1(a)m_2(b)n\kappa k_\infty), s) \Psi(h) \chi(\det(h))^{-1} dh \\ &\stackrel{(167)}{=} |\mu_1(b)|^{-3(s+\frac{1}{2})} \int_{U[m_2(b)](\mathbb{A})} \Upsilon(Q \cdot \iota(b^{-1}h, m_1(a)n\kappa k_\infty), s) \Psi(bb^{-1}h) \chi(\det(b^{-1}h))^{-1} dh \\ &\stackrel{(194)}{=} |\mu_1(b)|^{-3(s+\frac{1}{2})} J_\infty(\eta_0 k_\infty) \int_{U(1,1)(\mathbb{A})} \Upsilon(Q \cdot \iota(h, m_1(a)n\kappa), s) \Psi(bh) \chi(\det(h))^{-1} dh \\ &= \chi(a)|N(a)\mu_1(b)|^{-3(s+\frac{1}{2})} J_\infty(\eta_0 k_\infty) \int_{U(1,1)(\mathbb{A})} \Upsilon(Q \cdot \iota(h, \kappa), s) \Psi(bh) \chi(\det(h))^{-1} dh. \end{aligned}$$

Using the Whittaker expansion

$$\Psi(g) = \sum_{\lambda \in \mathbb{Q}^\times} W_\Psi \left( \begin{bmatrix} \lambda & 0 \\ 0 & 1 \end{bmatrix} g \right), \quad (218)$$

we have

$$\int_{\mathrm{U}(1,1)(\mathbb{A})} \Upsilon(Q \cdot \iota(h, \kappa), s) \Psi(bh) \chi(\det(h))^{-1} dh = \sum_{\lambda \in \mathbb{Q}^\times} Z\left(\begin{bmatrix} \lambda & 0 \\ 0 & 1 \end{bmatrix} b, s; \kappa\right), \quad (219)$$

where for  $g \in G_1(\mathbb{A})$ ,  $g_2 \in \mathrm{U}(2, 2)(\mathbb{A})$ ,

$$Z(g, s; g_2) = \int_{\mathrm{U}(1,1)(\mathbb{A})} \Upsilon(Q \cdot \iota(h, g_2), s) W_\Psi(gh) \chi(\det(h))^{-1} dh.$$

Note that the uniqueness of the Whittaker function implies  $Z(g, s; \kappa) = \prod_v Z_v(g_v, s, \kappa_v)$ , where the local zeta integral  $Z_v(g_v, s, \kappa_v)$  is defined by

$$Z_v(g_v, s, \kappa_v) = \int_{\mathrm{U}(1,1)(\mathbb{Q}_v)} \Upsilon(Q \cdot \iota(h, \kappa_v), s) W^{(0)}(g_v h) \chi_v(\det(h))^{-1} dh;$$

at the archimedean place we understand  $W^{(0)} = W_{l_1}$ . Hence, by Theorems 3.2.1 and 3.4.1,

$$\Upsilon_\Psi(g, s) = \chi(a)|N(a)\mu_1(b)^{-1}|^{3(s+1/2)} T(s) \Psi(b) J_\infty(\eta_0 k_\infty, s) \prod_{\substack{p < \infty \\ \tau_p \text{ ramified}}} J_p(\kappa_p), \quad (220)$$

where for a finite place  $p$  with  $\tau_p$  of conductor  $p^n$ ,  $n > 0$ ,

$$J_p(\kappa_p) = \begin{cases} 1 & \text{if } \kappa_p = \eta_0, \\ 0 & \text{otherwise.} \end{cases} \quad (221)$$

This proves (217) and hence completes the proof of the theorem.  $\blacksquare$

**3.5.2 Remark.** Pullback formulas in the spirit of Theorem 3.5.1 as a method to express complicated Eisenstein series on lower rank groups in terms of simpler Eisenstein series on higher rank groups have a long history. Garrett [16] used pullback formulas for Eisenstein series on symplectic groups to study the triple product  $L$ -function, as well as to establish the algebraicity of certain ratios of inner products of Siegel modular forms. Pullback formulas for Eisenstein series on unitary groups were first proved in a classical setting by Shimura [57]. Unfortunately, Shimura only considers certain special types of Eisenstein series in his work, which do not include ours except in the very specific case when  $\tau$  is unramified principal series at all finite places and holomorphic discrete series at infinity.

### 3.6 The second global integral representation

In Theorem 2.3.2 we supplied a global integral representation for  $L(s, \tilde{\pi} \times \tilde{\tau})$ . Using Theorem 3.5.1, we can modify it into a second integral representation that is more suitable for certain purposes. Let

$$R(s) = \frac{L(3s + 1, \tau \times \mathcal{AI}(\Lambda) \times \chi|_{F^\times})}{L(6s + 2, \chi_{L/F}\chi|_{F^\times}) L(6s + 3, \chi|_{F^\times}) \cdot T(s) \cdot Y_{l_1, p, q}(s) \cdot \prod_{v < \infty} Y_v(s)}, \quad (222)$$

where  $T(s)$  is defined by (211), the factors  $Y_v(s)$  for non-archimedean  $v$  are given by Theorem 2.2.1, and the archimedean factor  $Y_{l_1, p, q}(s)$  is given by Theorem 2.2.2. Note that  $R(s)$  has an obvious Euler product  $R(s) = \prod_v R_v(s)$ , and that  $R_v(s) = 1$  for all finite places  $v$  where  $\tau_v$  is unramified.

Recall the Eisenstein series  $E_\Upsilon(g, s)$  defined in (210). We define the normalized Eisenstein series

$$E_\Upsilon^*(g, s) = L(6s + 1, \chi|_{\mathbb{A}^\times})L(6s + 2, \chi_{L/F}\chi|_{\mathbb{A}^\times})L(6s + 3, \chi|_{\mathbb{A}^\times})E_\Upsilon(g, s). \quad (223)$$

Let  $Z_H$  and  $Z_{G_1}$  denote respectively the centers of  $H = \mathrm{GSp}_4$  and  $G_1 = \mathrm{GU}(1, 1)$ . Given any  $g \in G_1$  we define  $H[g]$  to be the subgroup of  $H$  consisting of elements  $h \in H$  with  $\mu_2(h) = \mu_1(g)$ . From Theorem 2.3.2 and Theorem 3.5.1 we get the following result.

**3.6.1 Theorem.** *Let  $\phi = \otimes \phi_v$  be a vector in the space of  $\pi$  such that  $\phi_v$  is unramified for all finite  $v$  and such that  $\phi_\infty$  is a vector of weight  $(-l, -l)$  in  $\pi_\infty$ . Let  $\Psi$  be as in Theorem 3.5.1. The following meromorphic functions are all equal,*

$$\begin{aligned} i) \quad & R(s)^{-1}B_\phi(1)L(3s + \frac{1}{2}, \tilde{\pi} \times \tilde{\tau}) \\ ii) \quad & \int_{Z_H(\mathbb{A})H(\mathbb{Q}) \backslash H(\mathbb{A})} \phi(h)\chi(\mu_2(h)) \int_{\mathrm{U}(1,1)(\mathbb{Q}) \backslash \mathrm{U}[h](\mathbb{A})} E_\Upsilon^*(\iota(g, h), s)\Psi(g)\chi(\det(g))^{-1} dg dh, \\ iii) \quad & \int_{Z_{G_1}(\mathbb{A})G_1(\mathbb{Q}) \backslash G_1(\mathbb{A})} \Psi(g)\chi\left(\frac{\mu_1(g)}{\det(g)}\right) \int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash H[g](\mathbb{A})} E_\Upsilon^*(\iota(g, h), s)\phi(h) dh dg. \end{aligned}$$

For future reference, we record the following result about the poles of  $E_\Upsilon^*(g, s)$ .

**3.6.2 Proposition.** *Assume that the number  $q$  defined in (46) is zero. Then  $E_\Upsilon^*(g, s)$  has no poles in the region  $0 \leq \mathrm{Re}(s) \leq \frac{1}{4}$  except possibly a simple pole at the point  $s = \frac{1}{6}$ ; this pole can exist only if  $\omega_\tau = 1$ .*

**Proof.** First, note that the Eisenstein series  $E_\Upsilon^*(g, s)$  on  $\mathrm{GU}(3, 3)$  has a pole at  $s_0$  if and only if its restriction to  $\mathrm{U}(3, 3)$ , which is an Eisenstein series on  $\mathrm{U}(3, 3)$ , has a pole at  $s = s_0$ . Now the proof of the main Theorem of [60] shows exactly what we want. However, the statement there is a little ambiguous and seems to also allow for a possible simple pole at  $s = 0$ , in addition to the one at  $s = \frac{1}{6}$ . So we sketch the proof of holomorphy at  $s = 0$  here for completeness. Let  $I_v(\chi, 0)$  be as defined in [60]; this space is completely reducible at each non-archimedean inert place  $v$  (it is the direct sum of two irreducible representations). Now, we may choose any one of these irreducible components and work through the proof exactly as in [60]. ■

## 4 Holomorphy of global $L$ -functions for $\mathrm{GSp}_4 \times \mathrm{GL}_2$

In this section we will prove that the global  $L$ -function  $L(s, \pi \times \tau)$  appearing in Theorem 2.4.3 is entire. Our main tools are the global integral representation Theorem 3.6.1 and Ichino's regularized Siegel-Weil formula for unitary groups, Theorem 4.1 of [26].

### 4.1 Preliminary considerations

Our goal is to prove the following theorem.

**4.1.1 Theorem. (Holomorphy for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$ )** *Let  $\pi = \otimes \pi_v$  be a cuspidal, automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$  with the properties enumerated in Theorem 2.4.3 and such that  $\pi$  is not a Saito-Kurokawa lift. Let  $\tau = \otimes \tau_v$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  such that  $\tau_p$  is unramified for the primes  $p$  dividing  $D$ . Then  $L(s, \pi \times \tau)$  is an entire function.*

The proof will be completed in Section 4.3 below. To begin with, note that  $\tau$  may be twisted by an unramified Hecke character of the form  $|\cdot|^t$  to make sure that  $\omega_\tau$  is of finite order. Such a twist will merely shift the argument of the  $L$ -function, because of the equation  $L(s, \pi \times \tau \times |\cdot|^t) = L(s+t, \pi \times \tau)$ . It is therefore sufficient to prove Theorem 4.1.1 under the following assumption, which we will make throughout this section.

$$\text{The central character } \omega_\tau \text{ of } \tau \text{ is of finite order.} \quad (224)$$

In particular, this means that the number  $q$  defined in (46) is zero. Since  $\varepsilon$ -factors never have any zeros or poles, it follows from the functional equation Theorem 2.4.3 that in order to prove Theorem 4.1.1, *it is enough to prove that  $L(s, \pi \times \tau)$  has no poles in the region  $\operatorname{Re}(s) \geq \frac{1}{2}$ .*

**Remark:** Recall that the hypothesis that  $\tau_p$  is unramified for the primes  $p$  dividing  $D$  was necessary for Theorem 2.4.3. This is the only reason for this hypothesis in Theorem 4.1.1; the following arguments work for general  $\tau$ . The restriction on  $\tau$  will be removed in Theorem 5.2.2.

Let  $L_f(s, \pi \times \tau)$  be the finite part of  $L(s, \pi \times \tau)$ , i.e.,

$$L_f(s, \pi \times \tau) = \prod_{p < \infty} L_p(s, \pi_p \times \tau_p).$$

**4.1.2 Lemma.** *The Dirichlet series defining  $L_f(s, \pi \times \tau)$  converges absolutely for  $\operatorname{Re}(s) > \frac{5}{4}$ .*

**Proof.** In fact, the Dirichlet series converges absolutely for  $\operatorname{Re}(s) > \frac{71}{64}$ . This follows directly from the global temperedness of  $\pi$  due to Weissauer [65] and the best known bound towards the Ramanujan conjecture for cusp forms on  $\operatorname{GL}_2$  due to Kim-Sarnak [29]. ■

As a consequence, we get the following.

**4.1.3 Lemma.** *The completed  $L$ -function  $L(s, \pi \times \tau)$  has no poles in the region  $\operatorname{Re}(s) > \frac{5}{4}$ .*

**Proof.** In view of Lemma 4.1.2, we only have to show that  $L_\infty(s, \pi \times \tau)$  has no poles in that region. In fact it turns out that  $L_\infty(s, \pi \times \tau)$  has no poles in the region  $\operatorname{Re}(s) > 1$ . To see this, first note that  $q, \mu$  are equal to zero by our assumption on  $\omega_\tau$ . Next, by the unitarizability of  $\tau_\infty$ , it follows that  $p$  is a non-negative integer when  $\tau_\infty$  is discrete series (or limit of discrete series) and  $p \in i\mathbb{R} \cup (-1, 1)$  if  $\tau_\infty$  is principal series. Also, we have  $l \geq 2$ . Now the holomorphy of  $L_\infty(s, \pi \times \tau)$  in the desired right-half plane follows from the tables following Corollary 2.2.3. ■

We will now use the second integral representation to reduce the possible set of poles to at most one point.

**4.1.4 Proposition.**  *$L(s, \pi \times \tau)$  has no poles in the region  $\operatorname{Re}(s) \geq \frac{1}{2}$  except possibly a simple pole at the point  $s = 1$ . This pole can exist only if  $\omega_\tau = 1$ .*

**Proof.** In Theorem 3.6.1, the functions  $\Psi, \Upsilon, \chi, R(s)$  all depend on a choice of an integer  $l_1$  such that  $\tau$  has a vector of weight  $l_1$ . We now make such a choice. If  $\tau_\infty$  is a principal series representation, then put  $l_1 = 0$  or  $1$  (exactly one of these weights occurs in  $\tau$ ). If  $\tau_\infty$  is a discrete series (or a limit of discrete series) representation, then put  $l_1 = p+1$ ; hence,  $l_1$  is the lowest weight of  $\tau_\infty$ .

With this choice, we can check by an explicit calculation that the function  $R(s)$  defined in (222) has no poles in the region  $0 \leq \operatorname{Re}(s) \leq \frac{1}{4}$ . Indeed, the only possible pole in that region can come from  $R_\infty(s)$ , and so it boils down to checking that the function  $T_\infty(s)$  defined in Theorem 3.4.1 and the function  $Y_{l,l_1,p,q}(s)$  defined in Theorem 2.2.2 are non-zero when  $0 \leq \operatorname{Re}(s) \leq \frac{1}{4}$ . It is easy to verify that this is true with our choice of  $l_1$ .

On the other hand, by Theorem 3.6.2, the only possible pole of  $E_\Upsilon^*(g, s)$  in the region  $0 \leq \operatorname{Re}(s) \leq \frac{1}{4}$  is at  $s = \frac{1}{6}$ ; this pole can occur only if  $\omega_\tau = 1$ . The result now follows from Theorem 3.6.1 and Lemma 4.1.3.  $\blacksquare$

## 4.2 Eisenstein series and Weil representations

In view of Proposition 4.1.4, we will now assume that  $\omega_\tau = 1$ , and that the integer  $l_1$  used in the definition of  $\Upsilon_\infty$  is equal to  $p + 1$  in the discrete series case, and 0 or 1 otherwise. By abuse of notation, we continue to use  $E_\Upsilon(g, s)$  to denote its restriction to  $\mathrm{U}(3, 3)(\mathbb{A})$ . Indeed, this restricted function is an Eisenstein series on  $\mathrm{U}(3, 3)(\mathbb{A})$ . For brevity, we will use  $G'_3$  to denote  $\mathrm{U}(3, 3)$ . Let  $K^{G'_3}$  denote the standard maximal compact subgroup of  $G'_3(\mathbb{A})$ . Let  $I(\chi, s)$  be the set of holomorphic vectors in the global induced representation defined analogously to  $I(\tilde{\chi}, s)$  as in (208), except that we are now dealing with functions on  $\mathrm{U}(3, 3)$  rather than  $\mathrm{GU}(3, 3)$ . In other words  $I(\chi, s)$  consists of the sections  $f^{(s)}$  on  $G'_3(\mathbb{A})$  such that

$$f^{(s)}(m(A, 1)ng, s) = |N(\det A)|^{3(s+\frac{1}{2})} \chi(\det(A)) f^{(s)}(g, s) \quad (225)$$

for all  $g \in G'_3(\mathbb{A})$ , and so that  $f^{(s)}$  is holomorphic (in the sense of [26, p. 251]). In particular, any such section can be written as a finite linear combination of standard sections with holomorphic coefficients. A key example of a standard section is simply the restriction of the previously defined  $\Upsilon(g, s)$  to  $\mathrm{U}(3, 3)$ .

Recall that  $\phi = \otimes \phi_v$  is a vector in the space of  $\pi$  such that  $\phi_v$  is unramified for all finite  $v$  and such that  $\phi_\infty$  is a vector of weight  $(-l, -l)$  in  $\pi_\infty$ . We have the following lemma.

**4.2.1 Lemma.** *Suppose that the Eisenstein series  $E_\Upsilon(g, s)$  on  $\mathrm{U}(3, 3)(\mathbb{A})$  has the property that for all  $g_1 \in \mathrm{U}(1, 1)(\mathbb{A})$ , we have*

$$\int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash \mathrm{Sp}_4(\mathbb{A})} \operatorname{Res}_{s=\frac{1}{6}} E_\Upsilon(\iota(g_1, h_1), s) \phi(h_1) dh_1 = 0. \quad (226)$$

*Then  $L(s, \pi \times \tau)$  is holomorphic at  $s = 1$ .*

**Proof.** By Theorem 3.6.1, the fact that  $R(s)$  has no pole at  $s = \frac{1}{6}$ , and the fact that

$$L(6s + 1, \chi|_{\mathbb{A}^\times}) L(6s + 2, \chi_{L/F} \chi|_{\mathbb{A}^\times}) L(6s + 3, \chi|_{\mathbb{A}^\times})$$

is finite and non-zero at  $s = \frac{1}{6}$ , it follows that if

$$\int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash H[g](\mathbb{A})} \operatorname{Res}_{s=\frac{1}{6}} E_\Upsilon(\iota(g, h), s) \phi(h) dh = 0 \quad \text{for all } g \in G_1(\mathbb{A}),$$

then  $L(s, \pi \times \tau)$  is holomorphic at  $s = 1$ . Suppose  $E_\Upsilon(g, s)$  has the property (226). If  $g \in G_1(\mathbb{A})$  with  $\mu_1(g) = m$ , we can write  $m = \lambda z k$  with  $\lambda \in \mathbb{Q}^\times$ ,  $z \in \mathbb{R}^+$ ,  $k \in \prod_{p < \infty} \mathbb{Z}_p^\times$ . It follows that we can write

$$g = \begin{bmatrix} 1 \\ \lambda \end{bmatrix} g_1 \begin{bmatrix} z^{1/2} \\ z^{1/2} \end{bmatrix} \begin{bmatrix} 1 \\ k \end{bmatrix}$$

with  $g_1 \in \mathrm{U}(1, 1)(\mathbb{A})$ . A similar decomposition holds for  $h$  with  $\mu_2(h) = m$ . Thus

$$E_\Upsilon(\iota(g, h), s))\phi(h) = E_\Upsilon(\iota(g_1, h_1), s))\phi(h_1)$$

with  $g_1, h_1$  belonging to  $\mathrm{U}(1, 1)(\mathbb{A})$ ,  $\mathrm{Sp}_4(\mathbb{A})$  respectively. The lemma follows.  $\blacksquare$

We will reinterpret the condition of the lemma in terms of Weil representations and theta liftings. Let  $(V, \mathcal{Q})$  be a non-degenerate Hermitian space over  $L$  of dimension 4. We identify  $\mathcal{Q}$  with a Hermitian matrix of size 4. Let  $\mathrm{U}(V)$  be the unitary group of  $V$ ; thus

$$\mathrm{U}(V)(\mathbb{Q}) = \{g \in \mathrm{GL}_4(L) \mid {}^t \bar{g} \mathcal{Q} g = \mathcal{Q}\}.$$

Let  $\chi$  be as above. Fix an additive character  $\psi$  as before. As described in [26], there is a Weil representation  $\omega_{\mathcal{Q}} = \omega_{\mathcal{Q}, \psi, \chi}$  of  $G'_3(\mathbb{A}) \times \mathrm{U}(V)(\mathbb{A})$  acting on the Schwartz space  $\mathcal{S}(V^3(\mathbb{A}))$ . The explicit formulas for the action can be found in [26, p. 246].

Let  $s_0 = \frac{1}{6}$ . Let  $S(V^3(\mathbb{A}))$  denote the space of  $K^{G'_3}$ -finite vectors in  $\mathcal{S}(V^3(\mathbb{A}))$ . Write  $\Pi(V)$  for the image of the  $G'_3(\mathbb{A})$  intertwining map from  $S(V^3(\mathbb{A}))$  to  $I(\chi, s_0)$  given by

$$\varphi \mapsto f_\varphi^{(s_0)},$$

where  $f_\varphi^{(s_0)}(g) = (\omega_{\mathcal{Q}}(g)\varphi)(0)$ . We can extend  $f_\varphi^{(s_0)}$  to a standard section  $f_\varphi^{(s)} \in I(\chi, s)$  via

$$f_\varphi^{(s)}(g, s) = |N(\det A)|^{3(s-s_0)} f_\varphi^{(s_0)}(g),$$

where we use the Iwasawa decomposition to write  $g = m(A, 1)nk$  with  $A \in \mathrm{GL}_3(\mathbb{A}_L)$ ,  $n$  in the unipotent radical of the Siegel parabolic subgroup, and  $k \in K^{G'_3}$ .

Next we deal with the local picture. Suppose that  $(V^{(v)}, \mathcal{Q}^{(v)})$  is a non-degenerate Hermitian space over  $L_v$  of dimension 4. Then we have the local Weil representation  $\omega_{\mathcal{Q}_v} = \omega_{\mathcal{Q}_v, \psi_v, \chi_v}$  of  $G'_3(\mathbb{Q}_v) \times \mathrm{U}(V^{(v)})(\mathbb{Q}_v)$  acting on the Schwartz space  $\mathcal{S}((V^{(v)})^3)$ . We define  $R(V^{(v)})$  to be the image of the  $G'_3(\mathbb{Q}_v)$  intertwining map from  $S((V^{(v)})^3)$  to  $I_v(\chi_v, s_0)$  given by

$$\varphi \mapsto f_\varphi^{(s_0)},$$

where  $f_\varphi^{(s_0)}(g) = (\omega_{\mathcal{Q}_v}(g)\varphi)(0)$ . The span of the various subspaces  $R(V^{(v)})$  of  $I_v(\chi_v, s_0)$  as  $V^{(v)}$  ranges over the various inequivalent non-degenerate Hermitian spaces over  $L_v$  of dimension 4 is well understood. The non-archimedean case is treated in [34] while the archimedean case is treated in [38]. For instance, the following result [34, Thm. 1.2] describes the case when  $v$  is non-archimedean and  $L_v$  is a field.

**4.2.2 Theorem. (Kudla–Sweet)** Suppose that  $v$  is non-archimedean and  $L_v$  is a field. Let  $V_1^{(v)}$  and  $V_2^{(v)}$  be the two inequivalent non-degenerate Hermitian vector spaces over  $L_v$  of dimension 4. Then  $R(V_1^{(v)})$  and  $R(V_2^{(v)})$  are distinct maximal submodules of  $I_v(\chi_v, s_0)$ , so that

$$I_v(\chi_v, s_0) = R(V_1^{(v)}) + R(V_2^{(v)}).$$

In the case when  $v$  is non-archimedean and  $L_v = F_v \oplus F_v$ , a similar result is provided by [34, Thm. 1.3], while the case  $v = \infty$  is dealt with in [38]. Now, let  $\mathcal{C} = \{V^{(v)}\}$  be a collection, over all places  $v$  of  $\mathbb{Q}$ , of local non-degenerate Hermitian spaces over  $L_v$  of dimension 4. Whenever  $v$  is non-archimedean and  $L_v$  is a field, there are two inequivalent choices for  $V^{(v)}$ . Each of these spaces has an isotropic vector [34, Lemma 5.2]. If  $v$  is non-archimedean and  $L_v = F_v \oplus F_v$ , then the “Galois” automorphism is given by  $(x_1, x_2) \mapsto (x_2, x_1)$ . In this case the resulting “norm” map from  $L_v$  to  $F_v$  is surjective. So there is only one isometry class for  $V^{(v)}$  and the “unitary” group of  $V^{(v)}$  is isomorphic to  $\mathrm{GL}_4(F_v)$ . Indeed, up to isometry, the space  $V^{(v)}$  is explicitly given by  $V^{(v)} = F_v^4 \oplus F_v^4$  with  $(a, b) = [{}^t a_1 \cdot b_2, {}^t a_2 \cdot b_1]$  where  $a = (a_1, a_2)$ ,  $b = (b_1, b_2)$ . Finally, if  $v = \infty$ , there are 5 such  $V^{(v)}$ , corresponding to spaces of signature  $(p, q)$  with  $p + q = 4$ . For any such collection  $\mathcal{C}$  as above, let  $\Pi(\mathcal{C})$  be the representation space defined by

$$\Pi(\mathcal{C}) = \otimes_v R(V^{(v)}).$$

The upshot of the local results from [34] and [38] is that the natural map from  $\bigoplus_{\mathcal{C}} \Pi(\mathcal{C})$  to  $I(\chi, s_0)$  is surjective; here the sum ranges over all inequivalent collections  $\mathcal{C}$  as above. Let  $\mathcal{A}(G'_3)$  denote the space of automorphic forms over  $G'_3(\mathbb{A})$ . Define  $A_{-1}$  to be the  $G'_3(\mathbb{A})$  intertwining map from  $I(\chi, s_0)$  to  $\mathcal{A}(G'_3)$  given by

$$f^{(s_0)} \longmapsto \mathrm{Res}_{s=s_0} E_{f(s)}(g, s).$$

We note here (see [26, p. 252]) that the residue of the Eisenstein series at some point  $s_0$  only depends on the section at  $s_0$ , so the above map is indeed well defined.

Next, for any local Hermitian space  $V^{(v)}$  as above, with  $v$  non-archimedean, let  $V_0^{(v)}$  denote the complementary space, which is defined to be the space of dimension 2 over  $L_v$  in the same Witt class as  $V^{(v)}$ . Note that such a space exists because (by our comments above)  $V^{(v)}$  always has an isotropic vector if  $v$  is non-archimedean. The subspace  $R(V_0^{(v)})$  of  $I_v(\chi_v, -s_0)$  is defined similarly as above. It turns out (see [26], [34]) that for any non-archimedean place  $v$ , the restriction of the intertwining operator maps  $R(V^{(v)})$  onto  $R(V_0^{(v)})$ . This identifies  $R(V_0^{(v)})$  as a quotient of  $R(V^{(v)})$ ; in fact it is the unique irreducible quotient of  $R(V^{(v)})$ . Moreover, if  $f^{(s_0)}$  is a factorizable section, and the local section at a non-archimedean place  $v$  lies in the kernel of the above map from  $R(V^{(v)})$  to  $R(V_0^{(v)})$ , then  $A_{-1}(f^{(s_0)}) = 0$ . This follows from [26, Lemma 6.1]; the lemma only states the result for the case that  $L_v$  is a field, but the same proof also works for the split case using the local results from [34, Sect. 7].

From the above discussion, we conclude that the map  $A_{-1}$  factors through the quotient

$$I_\infty(\chi_\infty, s_0) \otimes (\bigoplus \Pi(\mathcal{C}')) ,$$

where  $\mathcal{C}' = \{V_0^{(v)}\}$  runs over all inequivalent collections of local Hermitian spaces  $V_0^{(v)}$  of dimension 2 over  $L_v$  with  $v$  ranging over the *non-archimedean* places. (Compare [32, Prop. 4.2] for the analogous result in the symplectic case.) But we can say more. For any global Hermitian space  $V_0$  of dimension 2 over  $L$ , let  $\Pi(V_0)$  be the image of the  $G'_3(\mathbb{A})$  intertwining map from  $S(V_0^3(\mathbb{A}))$  to  $I(\chi, -s_0)$ . Note that (at each place, and hence globally)  $\Pi(V_0)$  is naturally a quotient (via the intertwining operator) of  $\Pi(V)$ , where  $V$  is the complementary global Hermitian space of dimension 4 over  $L$ , obtained by adding a split space of dimension 2 to  $V_0$ .

**4.2.3 Proposition.** *The map  $A_{-1}$  from  $I(\chi, s_0)$  to  $\mathcal{A}(G'_3)$  factors through  $\bigoplus_{V_0} \Pi(V_0)$  where  $V_0$  runs through all global Hermitian spaces of dimension 2 over  $L$ .*

**Proof.** We have already seen that the map  $A_{-1}$  factors through the quotient  $I_\infty(\chi_\infty, s_0) \otimes (\oplus \Pi(\mathcal{C}'))$ , where  $\mathcal{C}' = \{V_0^{(v)}\}$  runs over all inequivalent collections of local Hermitian spaces  $V_0^{(v)}$  of dimension 2 over  $L_v$  with  $v$  ranging over the non-archimedean places of  $\mathbb{Q}$ . The argument of [59, p. 363–364] takes care of the archimedean place, and we get that  $A_{-1}$  factors through  $\oplus \Pi(\mathcal{C}')$ , where  $\mathcal{C}' = \{V_0^{(v)}\}$  runs over all inequivalent collections of local Hermitian spaces  $V_0^{(v)}$  of dimension 2 over  $L_v$ ; here  $v$  ranges over all the places of  $\mathbb{Q}$  including  $\infty$ .

The question now is if there exists a global Hermitian space  $V_0$  whose localizations are precisely the local spaces  $\{V_0^{(v)}\}$  in the collection  $\mathcal{C}'$ . If such a global Hermitian space does not exist, then the collection  $\mathcal{C}'$  is called incoherent, otherwise it is called coherent. From the local results quoted above, we know that each  $\Pi(\mathcal{C}')$  is irreducible. Thus to complete the proof we only need to show that  $\Pi(\mathcal{C}')$  cannot be embedded in  $\mathcal{A}(G'_3)$  if  $\mathcal{C}'$  is incoherent.

The proof that such an embedding cannot exist is fairly standard. See, for instance [32, Thm. 3.1 (ii)], [33, Prop. 2.6] or [59, Cor. 4.1.12]. Thus, we will be brief. For any (global) Hermitian matrix  $\beta$  of size 3, let  $W_\beta : \mathcal{A}(G'_3) \rightarrow \mathbb{C}$  denote the  $\beta$ -th Fourier coefficient, defined by

$$W_\beta(f) = \int_{N_{12}(\mathbb{Q}) \backslash N_{12}(\mathbb{A})} f(nb)\psi(-\text{tr}(b\beta)) db.$$

Let  $\mathcal{D}$  be a non trivial embedding of  $\Pi(\mathcal{C}')$  in  $\mathcal{A}(G'_3)$  where  $\mathcal{C}'$  is incoherent, and put  $\mathcal{D}_\beta = W_\beta \circ \mathcal{D}$ . Then there must exist some  $\beta$  such that  $\mathcal{D}_\beta$  is non-zero. Moreover, if  $\mathcal{D}_\beta = 0$  for all  $\beta$  of rank  $\geq 2$ , then the argument of [33, Lemma 2.5] shows that  $D = 0$ . So there exists  $\beta$  with  $\text{rank}(\beta) \geq 2$  and  $\mathcal{D}_\beta \neq 0$ . By well-known results on the twisted Jacquet functor (see [26, Lemmas 5.1 and 5.2]), this implies that  $\beta$  is locally represented by  $\{V_0^{(v)}\}$  at each place  $v$ , i.e., there exists  $v_0^{(v)} \in (V_0^{(v)})^3$  such that  $(v_0^{(v)}, v_0^{(v)}) = \beta$ . Since the dimension of  $V_0^{(v)}$  is 2, this implies that such a  $\beta$  cannot be non-singular; thus  $\text{rank}(\beta) = 2$ . Hence  $\beta$  is (globally) equivalent to  $\begin{bmatrix} \beta_0 & \\ & 0 \end{bmatrix}$  where  $\beta_0$  is of size 2 and non-singular. Let  $\epsilon_v(V_0^{(v)}) = \pm 1$  denote the Hasse invariant of the local Hermitian space  $V_0^{(v)}$ . Since the collection  $\mathcal{C}'$  is incoherent, we have  $\prod_v \epsilon_v(V_0^{(v)}) = -1$ . On the other hand, because  $\beta$  is locally represented by  $\{V_0^{(v)}\}$ , and  $\text{rank}(\beta) = \dim(V_0^{(v)}) = 2$ , it follows that the matrix for  $V_0^{(v)}$  equals  $\beta_0$  for some suitable basis. But this means that  $\epsilon_v(V_0^{(v)}) = \epsilon_v(\beta_0)$ . So  $\prod_v \epsilon_v(V_0^{(v)}) = \prod_v \epsilon_v(\beta_0) = 1$ , a contradiction. ■

### 4.3 The Siegel-Weil formula and the proof of entireness

In the previous subsection, we proved that the map  $A_{-1}$  from  $I(\chi, s_0)$  to  $\mathcal{A}(G'_3)$  given by

$$f^{(s_0)} \longmapsto \text{Res}_{s=s_0} E_{f^{(s)}}(g, s)$$

factors through  $\oplus_{V_0} \Pi(V_0)$ , where  $V_0$  runs through all global Hermitian spaces of dimension 2 over  $L$ . It turns out that the same map is also given by a regularized theta integral. This is the content of the regularized Siegel-Weil formula, which we now recall. Let  $(V_0, \mathcal{Q}_0)$  be a global Hermitian space of dimension 2 over  $L$  and let  $(V, \mathcal{Q})$  be the global Hermitian space of dimension 4 over  $L$  obtained by adding a split space of dimension 2 to  $V_0$ . Note that the Witt index of  $V$  is at least 1, thus  $V$  cannot be anisotropic. Given  $\varphi_0 \in S(V_0^3(\mathbb{A}))$  we define the theta function

$$\Theta(g, h; \varphi_0) = \sum_{x \in V_0^3(\mathbb{Q})} \omega_{\mathcal{Q}_0}(g, h) \varphi_0(x). \quad (227)$$

This is a slowly increasing function on  $(G'_3(\mathbb{Q}) \backslash G'_3(\mathbb{A})) \times (\mathrm{U}(V_0)(\mathbb{Q}) \backslash \mathrm{U}(V_0)(\mathbb{A}))$ . If  $\mathcal{Q}_0$  is anisotropic, we define

$$I_{\mathcal{Q}_0}(g, \varphi_0) = \int_{\mathrm{U}(V_0)(\mathbb{Q}) \backslash \mathrm{U}(V_0)(\mathbb{A})} \Theta(g, h; \varphi_0) dh.$$

If  $\mathcal{Q}_0$  is isotropic, the above integral does not converge, so we define

$$I_{\mathcal{Q}_0}(g, \varphi_0) = c_\alpha^{-1} \int_{\mathrm{U}(V_0)(\mathbb{Q}) \backslash \mathrm{U}(V_0)(\mathbb{A})} \Theta(g, h; \omega_{\mathcal{Q}_0}(\alpha)\varphi_0) dh,$$

where  $\alpha, c_\alpha$  are defined as in Sect. 2 of [26]. In fact, in the convergent case, the second definition automatically equals the first, so we might as well use it in both the cases. Next, one has a map of Schwartz functions  $\pi_{\mathcal{Q}}^{\mathcal{Q}_0} \pi_K$  from  $S(V^3(\mathbb{A}))$  to  $K_0$ -invariant functions in  $S(V_0^3(\mathbb{A}))$ ; here  $K_0$  is the standard maximal compact subgroup of  $\mathrm{U}(V_0(\mathbb{A}))$ . We refer the reader to [26] for definitions and details. Let  $\varphi \in S(V^3(\mathbb{A}))$ . Let  $f_\varphi^{(s)} \in I(\chi, s)$  be the standard section attached to  $\varphi$  via the Weil representation. Then the regularized Siegel-Weil formula [26, Thm. 4.1] in this setting says the following.

**4.3.1 Theorem. (Ichino)** *We have*

$$\mathrm{Res}_{s=s_0} E_{f_\varphi^{(s)}}(g, s) = c I_{\mathcal{Q}_0}(g, \pi_{\mathcal{Q}}^{\mathcal{Q}_0} \pi_K \varphi)$$

for an explicit constant  $c$  depending only on the normalization of Haar measures.

Theorem 4.3.1 and Proposition 4.2.3 imply the following result.

**4.3.2 Proposition.** *Suppose that the Eisenstein series  $E_\Gamma(g, s)$  does not satisfy the property (226). Then there exists a Hermitian space  $(V_0, \mathcal{Q}_0)$  of dimension 2 over  $L$  and a  $K_0$ -invariant Schwartz function  $\varphi_0 \in S(V_0^3(\mathbb{A}))$  such that, for some  $g \in \mathrm{U}(1, 1)(\mathbb{A})$ ,*

$$\int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash \mathrm{Sp}_4(\mathbb{A})} I_{\mathcal{Q}_0}(\iota(g, h), \varphi_0) \phi(h) dh \neq 0.$$

We will now prove Theorem 4.1.1. In order to do so, it suffices to show that the conclusion of Proposition 4.3.2 leads to a contradiction. First note that, given Schwartz functions  $\varphi_1 \in S(V_0(\mathbb{A}))$ ,  $\varphi_2 \in S(V_0^2(\mathbb{A}))$ , we may form the Schwartz function  $\varphi_0 = \varphi_2 \otimes \varphi_1 \in S(V_0^3(\mathbb{A}))$  defined by  $\varphi(v_1, v_2, v_3) = \varphi_1(v_3)\varphi_2(v_1, v_2)$ . The space generated by linear combinations of functions of this type is the full Schwartz space  $S(V_0^3(\mathbb{A}))$ . Suppose that the conclusion of Proposition 4.3.2 holds. By the definition of  $I_{\mathcal{Q}_0}$  and the above discussion, it follows that we can find  $\varphi_1 \in S(V_0(\mathbb{A}))$ ,  $\varphi_2 \in S(V_0^2(\mathbb{A}))$  such that for some  $g \in \mathrm{U}(1, 1)(\mathbb{A})$ , we have

$$\int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash \mathrm{Sp}_4(\mathbb{A})} \int_{U(V_0)(\mathbb{Q}) \backslash U(V_0)(\mathbb{A})} \Theta(\iota(g, h), h'; \varphi_2 \otimes \varphi_1) \phi(h) dh' dh \neq 0. \quad (228)$$

For  $g = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in \mathrm{U}(1, 1)$  let  $\hat{g} = \begin{bmatrix} a & -b \\ -c & d \end{bmatrix}$ . It is easy to check that

$$\omega_{\mathcal{Q}_0}(\iota(g, h))(\varphi_2 \otimes \varphi_1) = \omega_{\mathcal{Q}_0}(h)\varphi_2 \otimes \omega_{\mathcal{Q}_0}(\hat{g})\varphi_1.$$

Here, we are abusing notation and using  $\omega_{\mathcal{Q}_0}$  to denote the Weil representation of  $G_i(\mathbb{A})$  on  $\mathcal{S}(V_0^i(\mathbb{A}))$  for various  $i$ . This gives the following factorization,

$$\Theta(\iota(g, h), h'; \varphi_2 \otimes \varphi_1) = \Theta(\hat{g}, h'; \varphi_1) \Theta(h, h'; \varphi_2). \quad (229)$$

Define the automorphic form  $\Theta(h'; \phi, \varphi_2)$  on  $\mathrm{U}(V_0)(\mathbb{Q}) \backslash \mathrm{U}(V_0)(\mathbb{A})$  by

$$\Theta(h'; \phi, \varphi_2) = \int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash \mathrm{Sp}_4(\mathbb{A})} \Theta(h, h'; \varphi_2) \phi(h) dh.$$

Equations (228) and (229) imply the following.

**4.3.3 Lemma.** *Suppose that the conclusion of Proposition 4.3.2 holds. Then there exists a Schwartz function  $\varphi_2 \in S(V_0^2(\mathbb{A}))$  such that the automorphic form  $\Theta(h'; \phi, \varphi_2)$  on  $\mathrm{U}(V_0)(\mathbb{A})$  is non-zero.*

We will now interpret the conclusion of this lemma in terms of theta liftings. Let  $V_0^*$  denote the 4-dimensional orthogonal space over  $\mathbb{Q}$  obtained by considering  $V_0$  as a space over  $\mathbb{Q}$  and composing the hermitian form on  $V_0$  with  $\mathrm{tr}_{L/\mathbb{Q}}$ . We have the following seesaw diagram (see [31, p. 252]) of dual reductive pairs.<sup>3</sup>

$$\begin{array}{ccc} \mathrm{U}(2, 2) & & \mathrm{O}(V_0^*) \\ | & \times & | \\ \mathrm{Sp}(4) & & \mathrm{U}(V_0) \end{array}$$

Note that, at each place,  $V_0^*$  is either the unique anisotropic space of dimension four, or the split quadratic space  $V_{2,2}$ . Let  $\pi_1$  be the representation of  $\mathrm{Sp}_4(\mathbb{A})$  generated by the restriction of  $\phi$  to  $\mathrm{Sp}_4(\mathbb{A})$ . By [41], we know that  $\pi_1$  is an irreducible, automorphic, cuspidal representation. Moreover,  $\pi_1$  is an anti-holomorphic discrete series representation at infinity. The above seesaw diagram and Lemma 4.3.3 imply that if the conclusion of Proposition 4.3.2 holds, then  $\pi_1$  has a non-zero theta lift to  $\mathrm{O}(V_0^*)$ .

However, if  $\pi_1$  has a non-zero theta lift to  $\mathrm{O}(V_0^*)$ , then  $V_0^*$  cannot be split at infinity. This is because there is no local archimedean theta lift of an anti-holomorphic discrete series representation from  $\mathrm{Sp}_4(\mathbb{R})$  to  $\mathrm{O}(2, 2)(\mathbb{R})$ , see [47]. This means there must be a non-archimedean place  $v$  where  $V_0^*$  is ramified. But this implies that  $\pi_1$  is also ramified at  $v$ ; else the local theta lift would be zero. However, we know that  $\pi_1$  is unramified at all finite places because  $\phi$  is right-invariant under  $\mathrm{Sp}_4(\mathbb{Z}_p)$  at all finite places  $p$ . This contradiction shows that the conclusion of Proposition 4.3.2 cannot hold. Therefore the Eisenstein series  $E_Y(g, s)$  on  $\mathrm{U}(3, 3)(\mathbb{A})$  has the property that, for all  $g \in \mathrm{U}(1, 1)(\mathbb{A})$ ,

$$\int_{\mathrm{Sp}_4(\mathbb{Q}) \backslash \mathrm{Sp}_4(\mathbb{A})} \mathrm{Res}_{s=\frac{1}{6}} E_Y(\iota(g, h), s) \phi(h) dh = 0,$$

and hence  $L(s, \pi \times \tau)$  is holomorphic at  $s = 1$ . This completes the proof of Theorem 4.1.1.

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<sup>3</sup>We would like to thank Paul Nelson for pointing this out to us.

## 5 Applications

As a special case of Langlands functoriality, one expects that automorphic forms on  $\mathrm{GSp}_4$  have a functorial transfer to automorphic forms on  $\mathrm{GL}_4$ , coming from the natural embedding of dual groups  $\mathrm{GSp}_4(\mathbb{C}) \subset \mathrm{GL}_4(\mathbb{C})$ . For generic automorphic representations on  $\mathrm{GSp}_4$  this transfer was established in [3]. There is also a conjectured functorial transfer from automorphic forms on  $\mathrm{PGSp}_4$  to automorphic forms on  $\mathrm{GL}_5$ , coming from the morphism  $\rho_5 : \mathrm{Sp}_4(\mathbb{C}) \rightarrow \mathrm{GL}_5(\mathbb{C})$  of dual groups, where  $\rho_5$  is the irreducible 5-dimensional representation of  $\mathrm{Sp}_4(\mathbb{C})$ . Here, we are going to show the existence of both these transfers for full level holomorphic cuspidal Siegel eigenforms. Note that the automorphic representation generated by such a Siegel modular form is not globally generic, since its archimedean component, a holomorphic discrete series representation, is non-generic.

We will use the transfer results to prove analytic properties of several  $L$ -functions related to Siegel modular forms. In the last subsection we will derive some special value results for  $\mathrm{GSp}_4 \times \mathrm{GL}_1$  and  $\mathrm{GSp}_4 \times \mathrm{GL}_2$   $L$ -functions.

### 5.1 The transfer theorems

In the following let  $\mathbb{A}$  be the ring of adeles of  $\mathbb{Q}$ . As before we write  $H$  for  $\mathrm{GSp}_4$ , considered as an algebraic group over  $\mathbb{Q}$ . Let  $\pi = \otimes \pi_v$  be a cuspidal, automorphic representation of  $H(\mathbb{A})$  with the following properties.

- $\pi$  has trivial central character.
- The archimedean component  $\pi_\infty$  is a holomorphic discrete series representation with scalar minimal  $K$ -type  $(l, l)$ , where  $l \geq 3$ .
- For each finite place  $p$ , the local representation  $\pi_p$  is unramified.

It is well known that every such  $\pi$  gives rise to a holomorphic cuspidal Siegel eigenform of degree 2 and weight  $l$  with respect to the full modular group  $\mathrm{Sp}_4(\mathbb{Z})$ ; see [2]. Conversely, every such eigenform generates an automorphic representation  $\pi$  as above (which is in fact irreducible; see [41]). Well-known facts about classical full-level Siegel modular forms show that the cuspidality condition implies  $l \geq 10$ . For the following lemma let  $\psi$  be the standard global additive character that was used in Theorem 2.3.2 and Theorem 3.5.1. Recall the definition of global Bessel models from Sect. 2.1.

**5.1.1 Lemma.** *Let  $\pi$  be as above, and let  $F$  be the corresponding Siegel cusp form. Assume that the Fourier expansion of  $F$  is given by*

$$F(Z) = \sum_S a(F, S) e^{2\pi i \operatorname{tr}(SZ)}, \quad (230)$$

where  $Z$  lies in the Siegel upper half space of degree 2, and  $S$  runs through  $2 \times 2$  positive definite, semi-integral, symmetric matrices. Then, given a positive integer  $D$  such that  $-D$  is a fundamental discriminant, the following are equivalent.

- i)  $a(F, S) \neq 0$  for some  $S$  with  $D = 4 \det(S)$ .
- ii)  $\pi$  has a Bessel model of type  $(S(-D), \Lambda, \psi)$ , where  $S(-D)$  is the matrix defined in (138), and where  $\Lambda$  is a character of the ideal class group (139) of  $L = \mathbb{Q}(\sqrt{-D})$ .

**Proof:** This follows from equation (4.3.4) in [15] (which is based on (1-26) of [58]).  $\blacksquare$

The second author has recently shown that condition i) of the lemma is always satisfied for some  $D$ ; see [51]. In fact, independently of whether  $F$  is an eigenform or not, there exist infinitely many non-zero Fourier coefficients  $a(F, S)$  such that  $D = 4 \det(S)$  is odd and squarefree (in which case  $-D$  is automatically a fundamental discriminant). The important fact for us to note is that *there always exists a positive integer  $D$  such that  $-D$  is a fundamental discriminant and such that  $\pi$  satisfies the hypotheses of Theorem 2.4.3.*

We shall write down the explicit form of the local parameters of the representations  $\pi_v$ . These are admissible homomorphisms from the local Weil groups to the dual group  $\mathrm{GSp}_4(\mathbb{C})$ . Note that the trivial central character condition implies that the image of each local parameter lies in  $\mathrm{Sp}_4(\mathbb{C})$ . As in [62] (1.4.3), the real Weil group  $W_{\mathbb{R}}$  is given by  $W_{\mathbb{R}} = \mathbb{C}^\times \sqcup j\mathbb{C}^\times$  with the rules  $j^2 = -1$  and  $zjz^{-1} = \bar{z}$  for  $z \in \mathbb{C}^\times$ . Then the parameter of  $\pi_\infty$  is given by

$$\mathbb{C}^\times \ni re^{i\theta} \mapsto \begin{bmatrix} e^{i(2l-3)\theta} & & & \\ & e^{i\theta} & & \\ & & e^{-i(2l-3)\theta} & \\ & & & e^{-i\theta} \end{bmatrix}, \quad j \mapsto \begin{bmatrix} & -1 & & \\ & & -1 & \\ 1 & & & \\ & & 1 & \end{bmatrix}. \quad (231)$$

For a finite place  $p$ , there exist unramified characters  $\chi_1, \chi_2$  and  $\sigma$  of  $\mathbb{Q}_p^\times$  such that  $\pi_p$  is the spherical component of a parabolically induced representation  $\chi_1 \times \chi_2 \rtimes \sigma$  (using the notation of [52]). If we identify characters of  $\mathbb{Q}_p^\times$  with characters of the local Weil group  $W_{\mathbb{Q}_p}$  via local class field theory, then the  $L$ -parameter of  $\pi_p$  is given by

$$W_{\mathbb{Q}_p} \ni w \mapsto \begin{bmatrix} \sigma(w)\chi_1(w) & & & \\ & \sigma(w)\chi_1(w)\chi_2(w) & & \\ & & \sigma(w)\chi_2(w) & \\ & & & \sigma(w) \end{bmatrix}. \quad (232)$$

The central character condition is  $\chi_1\chi_2\sigma^2 = 1$ , so that the image of this parameter lies in  $\mathrm{Sp}_4(\mathbb{C})$ . Now, let  $\Pi_\infty$  be the irreducible, admissible representation of  $\mathrm{GL}_4(\mathbb{R})$  with  $L$ -parameter (231). For a prime number  $p$ , let  $\Pi_p$  be the irreducible, admissible representation of  $\mathrm{GL}_4(\mathbb{Q}_p)$  with  $L$ -parameter (232). Then the irreducible, admissible representation

$$\Pi_4 := \otimes \Pi_v \quad (233)$$

of  $\mathrm{GL}_4(\mathbb{A})$  is our candidate representation for the transfer of  $\pi$  to  $\mathrm{GL}_4$ . Clearly,  $\Pi_4$  is self-contraredient.

**5.1.2 Theorem.** *Let  $\pi$  be a cuspidal automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$  as above, related to a cuspidal Siegel eigenform  $F$ . We assume that  $F$  is not of Saito-Kurokawa type. Then the admissible representation  $\Pi_4$  of  $\mathrm{GL}_4(\mathbb{A})$  defined above is cuspidal automorphic. Hence  $\Pi_4$  is a strong functorial lifting of  $\pi$ . This representation is symplectic, i.e., the exterior square  $L$ -function  $L(s, \Pi_4, \Lambda^2)$  has a pole at  $s = 1$ .*

**Proof.** We will use the converse theorem for  $\mathrm{GL}_4$  from [10], and therefore have to establish the “niceness” of the  $L$ -functions of twists of  $\Pi$  by cusp forms on  $\mathrm{GL}_1$  and  $\mathrm{GL}_2$ . As remarked above, there exists a positive integer  $D$  such that  $-D$  is a fundamental discriminant and such that

$\pi$  satisfies the hypotheses of Theorem 2.4.3; we will fix such a  $D$ . Let  $\tau = \otimes \tau_p$  be a cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  such that  $\tau_p$  is unramified for  $p|D$ . By definition of the candidate representation  $\Pi$ , the  $\mathrm{GL}_4 \times \mathrm{GL}_2$   $L$ -function  $L(s, \Pi_4 \times \tau)$  coincides with the  $\mathrm{GSp}_4 \times \mathrm{GL}_2$   $L$ -function  $L(s, \pi \times \tau)$ . Therefore, by Theorem 4.1.1, the  $L$ -function  $L(s, \Pi_4 \times \tau)$  has analytic continuation to an entire function. Moreover, by Theorem 2.4.3, it satisfies the functional equation

$$L(s, \Pi_4 \times \tau) = \varepsilon(s, \Pi_4 \times \tau) L(1 - s, \tilde{\Pi}_4 \times \tilde{\tau}). \quad (234)$$

We will next prove that  $L(s, \Pi_4 \times \tau)$  is bounded in vertical strips.<sup>4</sup> Consider the group  $\mathrm{GSp}_8$  and its Levi subgroup  $\mathrm{GL}_2 \times \mathrm{GSp}_4$ . One of the representations of the dual parabolic with Levi  $\mathrm{GL}_2(\mathbb{C}) \times \mathrm{GSp}_4(\mathbb{C})$  on the dual unipotent radical is the tensor product representation. This means that our  $L$ -function  $L(s, \pi \times \tau)$  is accessible via Langlands' method; see [36]. Now, Gelbart and Lapid proved that *any*  $L$ -function that is accessible via Langlands' method is meromorphic of finite order; this is Theorem 2 in [17]. Here, a function  $f : \mathbb{C} \rightarrow \mathbb{C}$  being of finite order means that there exist positive constants  $r, c, C$  such that

$$|f(z)| \leq C e^{c|z|^r} \quad \text{for all } z \in \mathbb{C}.$$

By the Phragmen-Lindelöf Theorem, if a holomorphic function of finite order is bounded on the left and right boundary of a vertical strip, then it is bounded on the entire vertical strip. For a large enough positive number  $M$ , our function  $L(s, \pi \times \tau)$  is bounded on  $\mathrm{Re}(s) = M$ , since it is given as a product of archimedean Euler factors, which are bounded on vertical lines, times a convergent Dirichlet series. By the functional equation,  $L(s, \pi \times \tau)$  is also bounded on  $\mathrm{Re}(s) = -M$ . It follows that  $L(s, \pi \times \tau)$  is bounded on  $-M \leq \mathrm{Re}(s) \leq M$ . This proves that  $L(s, \Pi_4 \times \tau)$  is bounded in vertical strips.

A similar argument applies to twists of  $\Pi_4$  by Hecke characters  $\chi$  of  $\mathbb{A}^\times$ . The required functional equation of  $L(s, \Pi_4 \times \chi) = L(s, \pi \times \chi)$  is provided by [30]. The holomorphy follows from Theorem 2.2 of [42].

By Theorem 2 of [10], there exists an automorphic representation  $\Pi' = \otimes \Pi'_v$  of  $\mathrm{GL}_4(\mathbb{A})$  such that  $\Pi'_\infty \cong \Pi_\infty$  and  $\Pi'_p \cong \Pi_p$  for all primes  $p \nmid D$ . We claim that in fact  $\Pi'_p \cong \Pi_p$  for *all* primes  $p$ ; this will prove that the candidate representation  $\Pi_4$  is automorphic (but not yet the cuspidality). To prove our claim, observe that we have the functional equations

$$L(s, \Pi_4) = \varepsilon(s, \Pi_4) L(1 - s, \tilde{\Pi}_4) \quad (235)$$

and

$$L(s, \Pi') = \varepsilon(s, \Pi') L(1 - s, \tilde{\Pi}'). \quad (236)$$

We have (235) because  $L(s, \Pi_4) = L(s, \pi)$  and  $\varepsilon(s, \Pi_4) = \varepsilon(s, \pi)$  by definition of  $\Pi_4$ , so that we can use Andrianov's classical theory; see [1]. We have (236) because  $\Pi'$  is an automorphic representation of  $\mathrm{GL}_4(\mathbb{A})$ . Dividing (235) by (236) and observing that the local factors outside  $D$  coincide, we obtain

$$\prod_{p|D} \frac{L(s, \Pi_p) L(1 - s, \tilde{\Pi}'_p) \varepsilon(s, \Pi'_p)}{L(s, \Pi'_p) L(1 - s, \tilde{\Pi}_p) \varepsilon(s, \Pi_p)} = 1. \quad (237)$$

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<sup>4</sup>We would like to thank Mark McKee for explaining this argument to us.

It follows from unique prime factorization that if  $p_1, \dots, p_r$  are distinct primes, and if  $R_1, \dots, R_r \in \mathbb{C}(X)$  are such that

$$\prod_{i=1}^r R_i(p_i^s) = 1 \quad \text{for all } s \in \mathbb{C}, \quad (238)$$

then the rational functions  $R_i$  are all constant. Hence, it follows from (237) that

$$\frac{L(s, \Pi_p)L(1-s, \tilde{\Pi}'_p)\varepsilon(s, \Pi'_p)}{L(s, \Pi'_p)L(1-s, \tilde{\Pi}_p)\varepsilon(s, \Pi_p)} \quad \text{is constant for each } p|D. \quad (239)$$

Fix a prime  $p|D$ , and write (239) as

$$\frac{1}{L(s, \Pi_p)} = c_p X^m \frac{L(1-s, \tilde{\Pi}'_p)}{L(s, \Pi'_p)L(1-s, \tilde{\Pi}_p)}, \quad (240)$$

where  $c_p$  is a constant,  $X = p^{-s}$ , and  $m$  is some exponent coming from the  $\varepsilon$ -factors. Let  $\alpha, \beta, \gamma, \delta$  be the Satake parameters of  $\Pi_p$ , so that

$$L(s, \Pi_p) = \frac{1}{(1-\alpha p^{-s})(1-\beta p^{-s})(1-\gamma p^{-s})(1-\delta p^{-s})}.$$

Substituting into (240), we obtain

$$\begin{aligned} & (1-\alpha X)(1-\beta X)(1-\gamma X)(1-\delta X) \\ &= (1-(\alpha p)^{-1}X^{-1})(1-(\beta p)^{-1}X^{-1})(1-(\gamma p)^{-1}X^{-1})(1-(\delta p)^{-1}X^{-1})c_p X^m \frac{L(1-s, \tilde{\Pi}'_p)}{L(s, \Pi'_p)} \\ &= (X - (\alpha p)^{-1})(X - (\beta p)^{-1})(X - (\gamma p)^{-1})(X - (\delta p)^{-1})c_p X^{m-4} \frac{L(1-s, \tilde{\Pi}'_p)}{L(s, \Pi'_p)}. \end{aligned}$$

Consider the zeros of the functions on both sides of this equation. On the left hand side, we have zeros exactly when  $X = p^s$  is equal to

$$\alpha^{-1}, \quad \beta^{-1}, \quad \gamma^{-1}, \quad \delta^{-1} \quad (241)$$

(with repetitions allowed). On the right hand side, the factor  $L(1-s, \tilde{\Pi}'_p)$  does not contribute any zeros, since local  $L$ -factors are never zero. The factor  $X^{m-4}$  might contribute the zero 0, but this zero does certainly not appear amongst the numbers (241). Then there are the obvious *possible* zeros when  $X$  equals

$$(\alpha p)^{-1}, \quad (\beta p)^{-1}, \quad (\gamma p)^{-1}, \quad (\delta p)^{-1}. \quad (242)$$

Recalling that  $\alpha, \beta, \gamma, \delta$  originate from the Satake parameters of a holomorphic Siegel cusp form, the Ramanujan conjecture for such modular forms, proven in [65], implies that  $|\alpha| = |\beta| = |\gamma| = |\delta| = 1$ . (Even without the full Ramanujan conjecture, known estimates as those in [46] would lead to the same conclusion.) Hence there is no overlap between the numbers in (241) and (242). It follows that the factor  $L(s, \Pi'_p)$  must contribute the zeros (241) for the right hand side. In particular,  $L(s, \Pi'_p)^{-1}$  is a polynomial in  $p^{-s}$  of degree 4, so that  $\Pi'_p$  is a spherical representation. And then, evidently, its Satake parameters are precisely  $\alpha, \beta, \gamma$  and  $\delta$ . This is equivalent to saying  $\Pi'_p \cong \Pi_p$ , proving our claim.

We now proved that the candidate representation  $\Pi_4 = \otimes \Pi_v$  is automorphic, and it remains to prove it is cuspidal. Assume that  $\Pi_4$  is not cuspidal; we will obtain a contradiction. Being not cuspidal,  $\Pi_4$  is a constituent of a globally induced representation from a proper parabolic subgroup of  $\mathrm{GL}_4$ . It follows that  $L(s, \Pi_4)$  is, up to finitely many Euler factors, of one of the following forms.

- i)  $L(s, \chi_1)L(s, \chi_2)L(s, \chi_3)L(s, \chi_4)$  with Hecke characters  $\chi_i$  of  $\mathbb{A}^\times$ .
- ii)  $L(s, \chi_1)L(s, \chi_2)L(s, \tau)$  with Hecke characters  $\chi_1, \chi_2$  of  $\mathbb{A}^\times$  and a cuspidal, automorphic representation  $\tau$  of  $\mathrm{GL}_2(\mathbb{A})$ .
- iii)  $L(s, \chi_1)L(s, \tau)$  with a Hecke character  $\chi_1$  of  $\mathbb{A}^\times$  and a cuspidal, automorphic representation  $\tau$  of  $\mathrm{GL}_3(\mathbb{A})$ .
- iv)  $L(s, \tau_1)L(s, \tau_2)$  with cuspidal, automorphic representations  $\tau_1, \tau_2$  of  $\mathrm{GL}_2(\mathbb{A})$ .

Note that all the characters and representations in this list must be unramified at every finite place, since the same is true for  $\Pi_4$ . If one of the cases i), ii) or iii) is true, then  $L(s, \Pi_4 \times \chi_1^{-1})$  has a pole. Since  $L(s, \Pi_4 \times \chi_1^{-1}) = L(s, \pi \times \chi_1^{-1})$  and we are assuming that  $F$  is not of Saito-Kurokawa type, this contradicts Theorem 2.2 of [42]. Hence we are in case iv). But then  $L(s, \Pi_4 \times \tilde{\tau}_1) = L(s, \pi \times \tilde{\tau}_1)$  has a pole, contradicting Theorem 4.1.1. This contradiction shows that  $\Pi_4$  must be cuspidal.

It remains to prove the last statement. Since  $\Pi_4$  is self-dual, it is well known that exactly one of the  $L$ -functions

$$L(s, \Pi_4, \Lambda^2) \quad \text{or} \quad L(s, \Pi_4, \mathrm{Sym}^2)$$

has a pole at  $s = 1$ . If  $L(s, \Pi_4, \mathrm{Sym}^2)$  would have a pole at  $s = 1$ , then  $\Pi_4$  would be a (strong) lifting from the split orthogonal group  $\mathrm{SO}_4$ ; see the Theorem on p. 680 of [19] and the comments thereafter. By Lemma 5.1.3 below, this is impossible. It follows that  $L(s, \Pi_4, \Lambda^2)$  has a pole at  $s = 1$ . ■

**5.1.3 Lemma.** *Let  $F$  and  $\pi = \otimes \pi_v$  be as in Theorem 5.1.2, and let  $\Pi_4$  be the resulting lifting to  $\mathrm{GL}_4(\mathbb{A})$ . Then there does not exist a cuspidal, automorphic representation  $\sigma$  of  $\mathrm{SO}_4(\mathbb{A})$  such that  $\Pi_4$  is a Langlands functorial lifting of  $\sigma$ .*

**Proof.** The obstruction comes from the archimedean place. Recall that the dual group of  $\mathrm{SO}_4$  is  $\mathrm{SO}_4(\mathbb{C})$ , which we realize as

$$\mathrm{SO}_4(\mathbb{C}) = \{g \in \mathrm{SL}_4(\mathbb{C}) \mid {}^t g \begin{bmatrix} & 1_2 \\ 1_2 & \end{bmatrix} g = \begin{bmatrix} & 1_2 \\ 1_2 & \end{bmatrix}\}.$$

Let  $\varphi : W_{\mathbb{R}} \rightarrow \mathrm{GL}_4(\mathbb{C})$  be the archimedean  $L$ -parameter given explicitly in (231). If  $\Pi_4$  would come from  $\mathrm{SO}_4$ , there would exist a matrix  $g \in \mathrm{GL}_4(\mathbb{C})$  such that

$$g\varphi(w)g^{-1} \in \mathrm{SO}_4(\mathbb{C}) \quad \text{for all } w \in W_{\mathbb{R}}.$$

Then  ${}^t(g\varphi(w)g^{-1}) \begin{bmatrix} & 1_2 \\ 1_2 & \end{bmatrix} (g\varphi(w)g^{-1}) = \begin{bmatrix} & 1_2 \\ 1_2 & \end{bmatrix}$  for all  $w \in W_{\mathbb{R}}$ , or equivalently

$${}^t\varphi(w)S\varphi(w) = S, \quad \text{where } S = {}^t g \begin{bmatrix} & 1_2 \\ 1_2 & \end{bmatrix} g.$$

Letting  $w$  run through non-zero complex numbers  $re^{i\theta}$  shows that  $S$  is of the form

$$S = \begin{bmatrix} & a & \\ & b & \\ a & & \end{bmatrix}.$$

But then letting  $w = j$  yields the contradiction  $-S = S$ . ■

We will next consider a backwards lifting of  $\Pi_4$  in order to obtain a globally generic, cuspidal, automorphic representation on  $\mathrm{GSp}_4(\mathbb{A})$  in the same  $L$ -packet as  $\pi$ .

**5.1.4 Theorem.** *Let  $F$  and  $\pi = \otimes \pi_v$  be as in Theorem 5.1.2. Then there exists a globally generic, cuspidal, automorphic representation  $\pi^g = \otimes \pi_v^g$  of  $\mathrm{GSp}_4(\mathbb{A})$  such that  $\pi_p^g \cong \pi_p$  for all primes  $p$ , and such that  $\pi_\infty^g$  is the generic discrete series representation of  $\mathrm{PGSp}_4(\mathbb{R})$  lying in the same  $L$ -packet as  $\pi_\infty$ . Any globally generic, cuspidal automorphic representation  $\sigma = \otimes \sigma_v$  of  $\mathrm{GSp}_4(\mathbb{A})$  such that  $\sigma_p \cong \pi_p$  for almost all  $p$  coincides with  $\pi^g$ .*

**Proof.** Let  $\Pi_4$  be the lifting of  $\pi$  to  $\mathrm{GL}_4$  constructed in Theorem 5.1.2. Since  $\Pi_4$  is symplectic, we can apply Theorem 4 of [20]. The conclusion is that there exists a non-zero representation  $\sigma = \sigma_1 \oplus \dots \oplus \sigma_m$  of  $\mathrm{PGSp}_4(\mathbb{A})$  such that each  $\sigma_i$  is globally generic, cuspidal, automorphic and weakly lifts to  $\Pi_4$ . By Theorem 9 of [20], there can be only one  $\sigma_i$ , i.e.,  $\sigma$  is itself irreducible. Note that “weak lift” in [20] includes the condition that the lift is functorial with respect to archimedean  $L$ -parameters (see [20], p. 733). In particular, the archimedean component of  $\sigma$  is the generic discrete series representation of  $\mathrm{PGSp}_4(\mathbb{R})$  lying in the same  $L$ -packet as  $\pi_\infty$ . Evidently, the local components  $\sigma_p$  and  $\pi_p$  are isomorphic for almost all primes  $p$ . It remains to show that this is the case for *all* primes  $p$ . This can be done by a similar argument as in the proof of Theorem 5.1.2. Dividing the functional equations for the degree 4  $L$ -functions  $L(s, \pi)$  and  $L(s, \sigma)$ , and comparing the resulting zeros at a particular prime  $p$ , shows first that  $L(s, \sigma_p)$  is a degree 4 Euler factor. Hence  $\sigma_p$  is an unramified representation. The same comparison of zeros then also implies that  $\sigma_p$  and  $\pi_p$  have the same Satake parameters. The last assertion follows from the strong multiplicity one result Theorem 9 of [20]. ■

With  $F$  and  $\pi$  as above, we constructed a strong functorial lifting of  $\pi$  to  $\mathrm{GL}_4$  with respect to the natural inclusion of dual groups  $\mathrm{Sp}_4(\mathbb{C}) \subset \mathrm{GL}_4(\mathbb{C})$ . Similarly, we will now produce a strong functorial lifting of  $\pi$  to  $\mathrm{GL}_5$  with respect to the morphism  $\rho_5 : \mathrm{Sp}_4(\mathbb{C}) \rightarrow \mathrm{GL}_5(\mathbb{C})$  of dual groups, where  $\rho_5$  is the irreducible 5-dimensional representation of  $\mathrm{Sp}_4(\mathbb{C})$ . Let  $L(s, \pi, \rho_5)$  be the degree 5 (standard)  $L$ -function of  $F$ . If the  $L$ -parameter at a prime  $p$  is given by (232), then

$$L(s, \pi_p, \rho_5) = \frac{1}{(1 - p^{-s})(1 - \chi_1(p)p^{-s})(1 - \chi_1^{-1}(p)p^{-s})(1 - \chi_2(p)p^{-s})(1 - \chi_2^{-1}(p)p^{-s})}. \quad (243)$$

**5.1.5 Theorem.** *Let  $F$  and  $\pi = \otimes \pi_v$  be as in Theorem 5.1.2. Then there exists a cuspidal, automorphic representation  $\Pi_5$  of  $\mathrm{GL}_5(\mathbb{A})$  such that*

$$L(s, \pi, \rho_5) = L(s, \Pi_5) \quad (244)$$

(equality of completed Euler products). The representation  $\Pi_5$  is a strong functorial lifting of  $\pi$  to  $\mathrm{GL}_5$  with respect to the morphism  $\rho_5 : \mathrm{Sp}_4(\mathbb{C}) \rightarrow \mathrm{GL}_5(\mathbb{C})$  of dual groups. Moreover,  $\Pi_5$  is orthogonal, i.e., the symmetric square  $L$ -function  $L(s, \Pi_5, \mathrm{Sym}^2)$  has a pole at  $s = 1$ .

**Proof.** A straightforward calculation verifies that

$$L_f(s, \Pi_4, \Lambda^2) = L_f(s, \pi, \rho_5) \zeta(s). \quad (245)$$

Here, the subscript  $f$  indicates that the Euler product defining the  $L$ -functions is taken over finite places only, and  $\zeta(s)$  denotes the Riemann zeta function. By Theorem 5.1.2, the function

$L_f(s, \Pi_4, \Lambda^2)$  has a simple pole at  $s = 1$ . It follows that  $L_f(s, \pi, \rho_5)$  is holomorphic and non-zero at  $s = 1$ . Together with [22], Theorem 2, we obtain that  $L_f(s, \pi, \rho_5)$  has no poles on  $\text{Re}(s) = 1$ . Now by [29], Theorem A,  $L(s, \Pi_4, \Lambda^2)$  is the  $L$ -function of an automorphic representation of  $\text{GSp}_6(\mathbb{A})$  of the form

$$\text{Ind}(\tau_1 \otimes \dots \otimes \tau_m) \quad (246)$$

where  $\tau_1, \dots, \tau_m$  are unitary, cuspidal, automorphic representations of  $\text{GL}_{n_i}(\mathbb{A})$ ,  $n_1 + \dots + n_m = 6$ . Since  $L_f(s, \Pi_4, \Lambda^2)$  has a simple pole at  $s = 1$ , it follows that exactly one of the  $\tau_i$ , say  $\tau_m$ , is the trivial representation of  $\text{GL}_1(\mathbb{A})$ . Cancelling out one zeta factor, we see that

$$L_f(s, \pi, \rho_5) = L_f(s, \tau_1) \dots L_f(s, \tau_{m-1}). \quad (247)$$

Observe that since  $\pi$  is unramified at every finite place, the same must be true for the  $\tau_i$ . If we had  $n_i = 1$  for some  $i$ , then  $L(s, \tau_i)$ , and therefore the right hand side of (246), would have a pole on  $\text{Re}(s) = 1$ . This contradicts the observation from above that  $L_f(s, \pi, \rho_5)$  has no poles on  $\text{Re}(s) = 1$ . Hence  $n_i > 1$  for all  $i$ , so that the only possibilities for the set  $\{n_1, \dots, n_{m-1}\}$  are  $\{2, 3\}$  and  $\{5\}$ . Assume the former is the case, so that, say,  $\tau_1$  is a cuspidal representation of  $\text{GL}_2(\mathbb{A})$  and  $\tau_2$  is a cuspidal representation of  $\text{GL}_3(\mathbb{A})$ . Let  $\Pi_5 = \text{Ind}(\tau_1 \otimes \tau_2)$ . It is not hard to verify that

$$L_f(s, \Pi_5, \Lambda^2) = L_f(s, \Pi_4, \text{Sym}^2), \quad (248)$$

which we know is an entire function. On the other hand,

$$L_f(s, \Pi_5, \Lambda^2) = L_f(s, \omega_{\tau_1}) L_f(s, \tau_1 \times \tau_2) L_f(s, \omega_{\tau_2} \times \tilde{\tau}_2), \quad (249)$$

where  $\omega_{\tau_i}$  is the central character of  $\tau_i$ . Since the latter is everywhere unramified, the right hand side of (249) has a pole on  $\text{Re}(s) = 1$ . This contradiction shows that the assumption  $\{n_1, \dots, n_{m-1}\} = \{2, 3\}$  must be wrong. Hence  $\Pi_5 := \tau_1$  is a cuspidal representation of  $\text{GL}_5(\mathbb{A})$  such that

$$L_f(s, \pi, \rho_5) = L_f(s, \Pi_5). \quad (250)$$

This implies that  $\Pi_5$  is a lifting of  $\pi$  (with respect to the morphism  $\rho_5$  of dual groups) at every finite place. At the archimedean place, observe that the  $L$ -parameter of  $\text{Ind}(\tau_1 \otimes \tau_2)$  equals the exterior square of the  $L$ -parameter of  $\Pi_4$ , since the lifting of [29] is strong. On the other hand, an explicit calculation shows that the exterior square of the  $L$ -parameter of  $\Pi_4$  equals the  $L$ -parameter of  $\pi$  composed with  $\rho_5$ , plus the trivial representation of  $W_{\mathbb{R}}$  (in other words, the archimedean place behaves exactly as the finite places, so that (245) holds in fact for the completed  $L$ -functions). Cancelling out the trivial representation on both sides, one obtains an equality of the  $L$ -parameter of  $\tau_1$  with the  $L$ -parameter of  $\pi$  composed with  $\rho_5$ . Hence  $\Pi_5$  is a functorial lifting of  $\pi$  also at the archimedean place.

Finally,  $\Pi_5$  is orthogonal since the exterior square  $L_f(s, \Pi_5, \Lambda^2)$  has no pole at  $s = 1$ ; see (248). This concludes the proof. ■

## 5.2 Analytic properties of $L$ -functions

For  $n \in \{1, 4, 5, 10, 14, 16\}$  let  $\rho_n$  be the  $n$ -dimensional irreducible representation of  $\text{Sp}_4(\mathbb{C})$ . In the notation of [14], Sect. 16.2. we have  $\rho_4 = \Gamma_{1,0}$ ,  $\rho_5 = \Gamma_{0,1}$ ,  $\rho_{10} = \Gamma_{2,0}$ ,  $\rho_{14} = \Gamma_{0,2}$  and  $\rho_{16} = \Gamma_{1,1}$ . Of course,  $\rho_4$  is the natural representation of  $\text{Sp}_4(\mathbb{C})$  on  $\mathbb{C}^4$ , which is also called the spin representation. An explicit formula for the representation  $\rho_5$  as a map  $\text{Sp}_4(\mathbb{C}) \rightarrow \text{SO}_5(\mathbb{C})$  is given in Appendix A.7

of [48]. (Somewhat confusingly, in the theory of Siegel modular forms  $\rho_5$  is often referred to as the standard representation, even though it is  $\rho_4$  that is the non-trivial representation of lowest dimension.) The representation  $\rho_{10}$  is the adjoint representation of  $\mathrm{Sp}_4(\mathbb{C})$  on its Lie algebra. We have the following relations,

$$\Lambda^2 \rho_4 = \rho_1 + \rho_5, \quad (251)$$

$$\Lambda^2 \rho_5 = \mathrm{Sym}^2 \rho_4 = \rho_{10}, \quad (252)$$

$$\mathrm{Sym}^2 \rho_5 = \rho_1 + \rho_{14}, \quad (253)$$

$$\rho_4 \otimes \rho_5 = \rho_4 + \rho_{16}. \quad (254)$$

Let  $F$  and  $\pi$  be as in Theorem 5.1.2. To each  $\rho_n$  we have an associated global  $L$ -function  $L(s, \pi, \rho_n)$ . We will list the archimedean  $L$ - and  $\varepsilon$ -factors (the latter with respect to the character  $\psi^{-1}$ , where  $\psi(x) = e^{-2\pi i x}$ ). Let  $\Gamma_{\mathbb{R}}$  and  $\Gamma_{\mathbb{C}}$  be as in (120). The archimedean factors depend only on the minimal  $K$ -type  $(l, l)$  of  $\pi_{\infty}$ .

$\rho$	$L(s, \pi_{\infty}, \rho)$	$\varepsilon(s, \pi_{\infty}, \rho, \psi^{-1})$
$\rho_1$	$\Gamma_{\mathbb{R}}(s)$	1
$\rho_4$	$\Gamma_{\mathbb{C}}(s + \frac{1}{2}) \Gamma_{\mathbb{C}}(s + l - \frac{3}{2})$	$(-1)^l$
$\rho_5$	$\Gamma_{\mathbb{R}}(s) \Gamma_{\mathbb{C}}(s + l - 1) \Gamma_{\mathbb{C}}(s + l - 2)$	1
$\rho_{10}$	$\Gamma_{\mathbb{R}}(s + 1)^2 \Gamma_{\mathbb{C}}(s + 1) \Gamma_{\mathbb{C}}(s + l - 1) \Gamma_{\mathbb{C}}(s + l - 2) \Gamma_{\mathbb{C}}(s + 2l - 3)$	1
$\rho_{14}$	$\Gamma_{\mathbb{R}}(s)^2 \Gamma_{\mathbb{C}}(s + 1) \Gamma_{\mathbb{C}}(s + l - 1) \Gamma_{\mathbb{C}}(s + l - 2)$ $\Gamma_{\mathbb{C}}(s + 2l - 2) \Gamma_{\mathbb{C}}(s + 2l - 3) \Gamma_{\mathbb{C}}(s + 2l - 4)$	1
$\rho_{16}$	$\Gamma_{\mathbb{C}}(s + \frac{1}{2})^2 \Gamma_{\mathbb{C}}(s + l - \frac{1}{2}) \Gamma_{\mathbb{C}}(s + l - \frac{3}{2})^2 \Gamma_{\mathbb{C}}(s + l - \frac{5}{2})$ $\Gamma_{\mathbb{C}}(2 + 2l - \frac{5}{2}) \Gamma_{\mathbb{C}}(2 + 2l - \frac{7}{2})$	-1

These factors are normalized so that they fit into a functional equation relating  $s$  and  $1 - s$ , and hence differ from the traditional factors used in the theory of Siegel modular forms. For example, the classical Andrianov spin  $L$ -function relates  $s$  and  $2l - 2 - s$ ; see [1], Theorem 3.1.1. To obtain the Andrianov  $\Gamma$ -factors, one has to replace  $s$  by  $s - l + \frac{3}{2}$  in the above factor for  $\rho_4$ .

**5.2.1 Theorem.** *Let  $F$  and  $\pi$  be as in Theorem 5.1.2. The Euler products defining the  $L$ -functions  $L_f(s, \pi, \rho_n)$ , for  $n \in \{4, 5, 10, 14, 16\}$ , are absolutely convergent for  $\mathrm{Re}(s) > 1$ . They have meromorphic continuation to the entire complex plane, have no zeros or poles on  $\mathrm{Re}(s) \geq 1$ , and the completed  $L$ -functions (using the above archimedean factors) satisfy the functional equation*

$$L(s, \pi, \rho_n) = \varepsilon(s, \pi, \rho_n) L(1 - s, \pi, \rho_n).$$

Furthermore, for  $n \in \{4, 5, 10\}$ , the functions  $L(s, \pi, \rho_n)$  are entire and bounded in vertical strips.

**Proof.** By definition,  $L(s, \pi, \rho_4) = L(s, \Pi_4)$  and  $L(s, \pi, \rho_5) = L(s, \Pi_5)$ . Hence, the analytic properties of  $L(s, \pi, \rho_4)$  and  $L(s, \pi, \rho_5)$  follow from the known analytic properties of  $L$ -functions of cuspidal representations on  $\mathrm{GL}_n$ . For the absolute convergence of the Euler products in  $\mathrm{Re}(s) > 1$ , see [28], Theorem 5.3. As for the adjoint  $L$ -function, it follows from (252) that

$$L(s, \Pi_4, \mathrm{Sym}^2) = L(s, \pi, \rho_{10}). \quad (255)$$

Since  $\Pi_4$  is symplectic by Theorem 5.1.2, this is an entire function; see [7, Thm. 7.5]. The absolute convergence in  $\mathrm{Re}(s) > 1$  follows from [28, Thm. 5.3], together with the known automorphy,

hence absolute convergence, of  $L(s, \Pi_4, \Lambda^2)$ . Since symmetric square  $L$ -functions are accessible via the Langlands-Shahidi method, the boundedness in vertical strips follows from [18], and the functional equation follows from [55, Cor. 6.7]. The non-vanishing on  $\operatorname{Re}(s) = 1$  follows also from the Langlands-Shahidi method; see Sect. 5 of [54]. From (253) we get

$$L(s, \Pi_5, \operatorname{Sym}^2) = Z(s)L(s, \pi, \rho_{14}), \quad (256)$$

where  $Z(s) = \Gamma_{\mathbb{R}}(s)\zeta(s)$  is the completed Riemann zeta function. Observe that  $L(s, \Pi_5, \Lambda^2)$  is absolutely convergent for  $\operatorname{Re}(s) > 1$  by (248). Together with [28], Theorem 5.3, this implies the absolute convergence of  $L(s, \Pi_5, \operatorname{Sym}^2)$ , and hence of  $L(s, \pi, \rho_{14})$ , in  $\operatorname{Re}(s) > 1$ . The meromorphic continuation of  $L(s, \pi, \rho_{14})$  is obvious from (256). Since this is an identity of complete Euler products, and since our liftings are strongly functorial, it also implies the asserted functional equation. By Theorem 5.1.5 the function  $L(s, \Pi_5, \operatorname{Sym}^2)$  has a simple pole at  $s = 1$ , while otherwise it is holomorphic and non-vanishing on  $\operatorname{Re}(s) = 1$ . Since the same is true for  $Z(s)$ , it follows that  $L(s, \pi, \rho_{14})$  is holomorphic and non-vanishing on  $\operatorname{Re}(s) = 1$ . Since

$$L(s, \Pi_4 \times \Pi_5) = L(s, \pi)L(s, \pi, \rho_{16}). \quad (257)$$

by (254), similar arguments apply to  $L(s, \pi, \rho_{16})$ . ■

Let  $r$  be a positive integer, and  $\tau$  a cuspidal, automorphic representation of  $\operatorname{GL}_r(\mathbb{A})$ . Let  $\sigma_r$  be the standard representation of the dual group  $\operatorname{GL}_r(\mathbb{C})$ . Then we can consider the Rankin-Selberg Euler products  $L(s, \pi \times \tau, \rho_n \otimes \sigma_r)$ , where  $\rho_n$  is one of the irreducible representations of  $\operatorname{Sp}_4(\mathbb{C})$  considered above. For  $n = 4$  or  $n = 5$ , since  $\Pi_4$  and  $\Pi_5$  are functorial liftings of  $\pi$ , we have

$$L(s, \pi \times \tau, \rho_n \otimes \sigma_r) = L(s, \Pi_n \times \tau), \quad (258)$$

where the  $L$ -function on the right is a standard Rankin-Selberg  $L$ -function for  $\operatorname{GL}_n \times \operatorname{GL}_r$ . From the well-known properties of these  $L$ -functions, the following result is immediate. For  $\varepsilon > 0$  and a closed interval  $I$  on the real line we use the notation  $T_{\varepsilon, I} = \{s \in \mathbb{C} \mid \operatorname{Re}(s) \in I, |\operatorname{Im}(s)| \geq \varepsilon\}$ , as in [18].

**5.2.2 Theorem.** *Let  $F$  and  $\pi$  be as in Theorem 5.1.2. Let  $r$  be a positive integer, and  $\tau$  a (unitary) cuspidal, automorphic representation of  $\operatorname{GL}_r(\mathbb{A})$ . Let  $n = 4$  or  $n = 5$ . Then the Euler products defining the  $\operatorname{GSp}_4 \times \operatorname{GL}_r$   $L$ -functions  $L(s, \pi \times \tau, \rho_n \otimes \sigma_r)$  are absolutely convergent for  $\operatorname{Re}(s) > 1$ . They have meromorphic continuation to the entire complex plane, and the completed  $L$ -functions satisfy the functional equation*

$$L(s, \pi \times \tau, \rho_n \otimes \sigma_r) = \varepsilon(s, \pi \times \tau, \rho_n \otimes \sigma_r)L(1 - s, \tilde{\pi} \times \tilde{\tau}, \rho_n \otimes \sigma_r). \quad (259)$$

These  $L$ -functions are entire, bounded in vertical strips, and non-vanishing on  $\operatorname{Re}(s) \geq 1$ , except in the cases

- $n = r = 4$  and  $\tau = |\det|^{it} \otimes \Pi_4$ , where  $t \in \mathbb{R}$  and  $\Pi_4$  is the lifting of  $\pi$  from Theorem 5.1.2, or
- $n = r = 5$  and  $\tau = |\det|^{it} \otimes \Pi_5$ , where  $t \in \mathbb{R}$  and  $\Pi_5$  is the lifting of  $\pi$  from Theorem 5.1.5.

In these cases the function  $L(s, \pi \times \tau, \rho_n \otimes \sigma_r)$  is holomorphic except for simple poles at  $s = -it$  and  $s = 1 - it$ , and is bounded on all sets of the form  $T_{\varepsilon, I}$  with  $\varepsilon > |t|$ .

**Proof.** For the precise location of poles, see Theorem 2.4 of [11]. For boundedness in vertical strips, see Corollary 2 on p. 80 of [18].  $\blacksquare$

**5.2.3 Theorem.** Let  $F$  and  $F'$  be Siegel cusp forms with respect to  $\mathrm{Sp}_4(\mathbb{Z})$ . Assume that  $F$  and  $F'$  are Hecke eigenforms, that they are not Saito-Kurokawa lifts and that  $\pi$  resp.  $\pi'$  are the associated cuspidal, automorphic representations of  $\mathrm{GSp}_4(\mathbb{A})$ . Let  $n \in \{4, 5\}$  and  $n' \in \{4, 5\}$ . Then the Euler products defining the  $\mathrm{GSp}_4 \times \mathrm{GSp}_4$   $L$ -functions  $L(s, \pi \times \pi', \rho_n \otimes \rho_{n'})$  are absolutely convergent for  $\mathrm{Re}(s) > 1$ . They have meromorphic continuation to the entire complex plane, and the completed  $L$ -functions satisfy the expected functional equation. These functions are entire, bounded in vertical strips, and non-vanishing on  $\mathrm{Re}(s) \geq 1$ , except if  $n = n'$  and  $F$  and  $F'$  have the same Hecke eigenvalues. In these cases the function  $L(s, \pi \times \pi', \rho_n \otimes \rho_{n'})$  is holomorphic except for simple poles at  $s = 0$  and  $s = 1$ , and is bounded on all sets of the form  $T_{\varepsilon, I}$  with  $\varepsilon > 0$ .

**Proof.** By definition,

$$L(s, \pi \times \pi', \rho_n \otimes \rho_{n'}) = L(s, \Pi_n \times \Pi'_{n'}), \quad (260)$$

where  $\Pi_n$  (resp.  $\Pi'_{n'}$ ) is the lifting of  $\pi$  (resp.  $\pi'$ ) to  $\mathrm{GL}_n$  (resp.  $\mathrm{GL}_{n'}$ ). Evidently,  $F$  and  $F'$  have the same Hecke eigenvalues if and only if  $\pi$  and  $\pi'$  are nearly equivalent if and only if  $\Pi_n = \Pi'_{n'}$ . Hence everything follows from the properties of  $L$ -functions for  $\mathrm{GL}_n \times \mathrm{GL}_{n'}$ .  $\blacksquare$

**5.2.4 Theorem.** Let  $F$  and  $F'$  be Siegel cusp forms with respect to  $\mathrm{Sp}_4(\mathbb{Z})$ . Assume that  $F$  and  $F'$  are Hecke eigenforms, that they are not Saito-Kurokawa lifts and that  $\pi$  resp.  $\pi'$  are the associated cuspidal, automorphic representations of  $\mathrm{GSp}_4(\mathbb{A})$ . Let  $\chi$  be a Hecke character of  $\mathbb{A}^\times$  (possibly trivial) such that  $\chi^2 = 1$ ,  $\tau_2$  be a unitary, cuspidal, automorphic representation of  $\mathrm{GL}_2(\mathbb{A})$  with trivial central character, and  $\tau_3$  be a unitary, self-dual, cuspidal, automorphic representation of  $\mathrm{GL}_3(\mathbb{A})$ . Then the central values

$$L(1/2, \pi \otimes \chi, \rho_4), \quad L(1/2, \pi \otimes \tau_2, \rho_5 \otimes \sigma_2), \quad L(1/2, \pi \otimes \tau_3, \rho_4 \otimes \sigma_3), \quad L(1/2, \pi \times \pi', \rho_4 \otimes \rho_5),$$

are all non-negative.

**Proof.** Recall that the lifting  $\Pi_4$  is symplectic by Theorem 5.1.2, and the lifting  $\Pi_5$  is orthogonal by Theorem 5.1.5. Furthermore,  $\tau_2$  is symplectic and  $\tau_3$  is orthogonal. All the assertions now follow from Theorem 1.1 of [37].  $\blacksquare$

### 5.3 Critical values of $L$ -functions

If  $L(s, \mathcal{M})$  is an arithmetically defined (or motivic)  $L$ -series associated to an arithmetic object  $\mathcal{M}$ , it is of interest to study its values at certain critical points  $s = m$ . For these critical points, conjectures due to Deligne predict that  $L(m, \mathcal{M})$  is the product of a suitable transcendental number  $\Omega$  and an algebraic number  $A(m, \mathcal{M})$  and furthermore, if  $\sigma$  is an automorphism of  $\mathbb{C}$ , then  $A(m, \mathcal{M})^\sigma = A(m, \mathcal{M}^\sigma)$ . In this subsection, we will prove critical value results in the spirit of the above conjecture for  $L$ -functions associated to a Siegel cusp form of full level.

For any subring  $A \subset \mathbb{C}$ , let  $S_l(\mathrm{Sp}_4(\mathbb{Z}), A)$  be the  $A$ -module consisting of the holomorphic Siegel cusp forms  $F(Z) = \sum_S a(F, S) e^{2\pi i \mathrm{tr}(SZ)}$  of weight  $l$  for  $\mathrm{Sp}_4(\mathbb{Z})$  for which all the Fourier coefficients

$a(F, S)$  lie in  $A$ . For  $F \in S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{C})$  and  $\sigma \in \mathrm{Aut}(\mathbb{C})$ , define  ${}^\sigma F$  by

$${}^\sigma F(Z) = \sum_S \sigma(a(F, S)) e^{2\pi i \mathrm{tr}(SZ)}.$$

By work of Shimura [56], we know that  ${}^\sigma F \in S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{C})$  and

$$S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{Q}) \otimes_{\mathbb{Q}} \mathbb{C} = S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{C}).$$

Also, if  $F$  is a Hecke eigenform, so is  ${}^\sigma F$ ; see Kurokawa [35].

Now, let  $F \in S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{C})$  be an eigenform for all the Hecke operators and let  $\pi_F$  be the associated cuspidal, automorphic representation of  $\mathrm{GSp}_4(\mathbb{A})$ . We assume that  $F$  is not of Saito-Kurokawa type, so that the hypothesis of Theorems 5.1.2 is satisfied. Let  $\Pi_F$  be the resulting cuspidal, automorphic representation of  $\mathrm{GL}_4(\mathbb{A})$ . The representation  $\Pi_F$  is regular and algebraic in the sense of [9]. We define the  $\sigma$ -twist  ${}^\sigma \Pi_F$  as in [9] or [63]. This can be described locally. If  $\Pi_F = \otimes_p \Pi_{F,p} \otimes \Pi_{F,\infty}$ , then  ${}^\sigma \Pi_F = \otimes_p {}^\sigma \Pi_{F,p} \otimes \Pi_{F,\infty}$ , where for any finite place  $p$ ,

$$\mathrm{Ind}_{B(\mathbb{Q}_p)}^{\mathrm{GL}_4(\mathbb{Q}_p)}(\chi_1 \otimes \dots \otimes \chi_4) = \mathrm{Ind}_{B(\mathbb{Q}_p)}^{\mathrm{GL}_4(\mathbb{Q}_p)}({}^\sigma \chi'_1 \otimes \dots \otimes {}^\sigma \chi'_4). \quad (261)$$

Here  $B$  is the standard Borel of  $\mathrm{GL}_4$ ,  $\chi_1, \dots, \chi_4$  are characters of  $\mathbb{Q}_p^\times$  and for any such  $\chi$ ,

$${}^\sigma \chi'(x) = \sigma(\chi(x)|x|^{\frac{1}{2}})|x|^{-\frac{1}{2}}.$$

(See Waldspurger's example on [63, p. 125].) We have the following lemma.

**5.3.1 Lemma.** *Let  $F$  be a holomorphic Siegel cusp form for  $\mathrm{Sp}_4(\mathbb{Z})$  that is an eigenfunction for all the Hecke operators and  $\sigma$  an automorphism of  $\mathbb{C}$ . Suppose that  $F$  is not of Saito-Kurokawa type. Then  ${}^\sigma F$  is not of Saito-Kurokawa type. Furthermore, if  $\Pi_{\sigma F}$  is the cuspidal, automorphic representation of  $\mathrm{GL}_4(\mathbb{A})$  obtained from  ${}^\sigma F$  by Theorem 5.1.2, then*

$$\Pi_{\sigma F} = {}^\sigma \Pi_F.$$

**Proof.** First of all, note that the condition of  $F$  being of Saito-Kurokawa type is equivalent to simple relations among the Fourier coefficients of  $F$  as in [13, p. 76]. These relations are preserved under the action of  $\sigma$ . This proves the first part of the lemma. For the second part, we need to show that  $\Pi_{\sigma F,p} = {}^\sigma \Pi_{F,p}$  for any prime  $p$ . Fix such a prime  $p$ . Suppose that

$$\Pi_{\sigma F,p} = \mathrm{Ind}_{B(\mathbb{Q}_p)}^{\mathrm{GL}_4(\mathbb{Q}_p)}(\chi''_1 \otimes \dots \otimes \chi''_4).$$

Let  $\lambda_{F,m}$  be the eigenvalue for the Hecke operator  $T(m)$  acting on  $F$ . For the exact definition of these Hecke operators, we refer the reader to Andrianov [1]. By Kurokawa [35], we know that  $\sigma(\lambda_{F,m}) = \lambda_{\sigma F,m}$ . By writing the local degree-4 Euler factors in terms of the Hecke eigenvalues, we conclude that the multisets  $\{\chi''_1(p), \dots, \chi''_4(p)\}$  and  $\{{}^\sigma \chi'_1(p), \dots, {}^\sigma \chi'_4(p)\}$  are identical. Hence

$$\mathrm{Ind}_{B(\mathbb{Q}_p)}^{\mathrm{GL}_4(\mathbb{Q}_p)}(\chi''_1 \otimes \dots \otimes \chi''_4) = \mathrm{Ind}_{B(\mathbb{Q}_p)}^{\mathrm{GL}_4(\mathbb{Q}_p)}({}^\sigma \chi'_1 \otimes \dots \otimes {}^\sigma \chi'_4),$$

and therefore,  $\Pi_{\sigma F} = {}^\sigma \Pi_F$ . ■

We now supply certain results on critical  $L$ -values for  $\mathrm{GSp}_4 \times \mathrm{GL}_n$  where  $n \in \{1, 2\}$ .

### Critical value result for $\mathrm{GSp}_4 \times \mathrm{GL}_1$

In [23], Grobner and Raghuram define certain periods of automorphic forms on  $\mathrm{GL}_{2n}$  by comparing cohomologies in top degree. We refrain from giving the definition of these periods here in the interest of brevity and instead refer the reader to [23, Sec. 4] for details. When the results of [23] are combined with our Theorem 5.1.2, we obtain a special value result for twists of Siegel eigenforms by Dirichlet characters. We now briefly describe this result.

Let  $F$  be a holomorphic Siegel cusp form of weight  $l$  for  $\mathrm{Sp}_4(\mathbb{Z})$  that is an eigenfunction for all the Hecke operators and is not of Saito-Kurokawa type. Let  $\Pi_F = \Pi_{F,f} \otimes \Pi_{F,\infty}$  be the lift to  $\mathrm{GL}_4(\mathbb{A})$ ; here  $\Pi_{F,f}$  denotes the finite part of the automorphic representation  $\Pi_F$ . Let  $\mathbb{Q}(\Pi_F)$  denote the rationality field of  $\Pi_F$  as defined in [9]. This is a totally real number field, and by the argument of Lemma 5.3.1, we know that  $\mathbb{Q}(\Pi_F)$  equals the field generated by all the Hecke eigenvalues of  $F$ . For convenience we will denote  $\mathbb{Q}(\Pi_F)$  by  $\mathbb{Q}(F)$ . For  $\chi$  a Hecke character of  $\mathbb{A}$  of finite order, let  $\mathbb{Q}(\chi)$  denote the number field generated by the image of  $\chi$  and let  $\mathbb{Q}(F, \chi)$  denote the compositum of  $\mathbb{Q}(F)$  and  $\mathbb{Q}(\chi)$ . Define  $\mathbb{Q}({}^\sigma F)$ ,  $\mathbb{Q}({}^\sigma \chi)$  and  $\mathbb{Q}({}^\sigma F, {}^\sigma \chi)$  similarly.

**5.3.2 Remark.** By Mizumoto [40], it is known that for any integer  $l$ , there exists an orthogonal basis  $\{F_1, F_2, \dots, F_d\}$  comprising of Hecke eigenfunctions for  $S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{C})$  such that each  $F_i \in S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{Q}(F_i))$ .

Let  $\omega^+(\Pi_{F,f})$  and  $\omega^-(\Pi_{F,f})$  be the periods as defined in [23, Sect. 4]. For convenience, let us denote them by  $\omega^+(F)$  and  $\omega^-(F)$  respectively. These are non-zero complex numbers obtained from comparing cohomologies in top degree. We also assume that Hypothesis 6.6.2 of [23] holds, and denote  $c(\Pi_{F,\infty}, 0)^{-1}$  by  $\omega_\infty(l)$ ; this notation is justified because  $c(\Pi_{F,\infty}, 0)$  depends only on the weight  $l$ . Then, applying the main theorem of [23] to the representation  $\Pi_F$  leads to the following special value result.

**5.3.3 Theorem. ([23], Corollary 8.3.1)** *Let  $F$  be a cuspidal Siegel eigenform of weight  $l$  for  $\mathrm{Sp}_4(\mathbb{Z})$  that is not of Saito-Kurokawa type and let  $\chi$  be a Hecke character of  $\mathbb{A}$  of finite order. Let  $\epsilon_\chi \in \{+, -\}$  denote the sign of  $\chi(-1)$ ,  $\mathcal{G}(\chi_f)$  denote the Gauss sum for  $\chi$  and  $L(s, \pi_{F,f} \times \chi_f) = \prod_{p < \infty} L(s, \pi_{F,p} \times \chi_p)$  denote the finite part of the  $L$ -function. Assume that Hypothesis 6.6.2 of [23] holds, and define*

$$A(F, \chi) = \frac{L(\frac{1}{2}, \pi_{F,f} \times \chi_f)}{\omega^{\epsilon_\chi}(F) \omega_\infty(l) \mathcal{G}(\chi_f)^2}.$$

Then we have

- i)  $A(F, \chi) \in \mathbb{Q}(F, \chi)$ ,
- ii) For any automorphism  $\sigma$  of  $\mathbb{C}$ , we have  $\sigma(A(F, \chi)) = A({}^\sigma F, {}^\sigma \chi)$ .

**5.3.4 Remark.** In [25], Harris defined certain ‘‘occult’’ periods for  $\mathrm{GSp}_4$  by comparing rational structures on Bessel models and rational structures on coherent cohomology and used these to study the critical values of the degree 4  $L$ -function for  $\mathrm{GSp}_4$ .

As a corollary to Theorem 5.3.3, we immediately obtain the following result.

**5.3.5 Corollary.** *Let  $d_1$  and  $d_2$  be two fundamental discriminants of the same sign, and let  $\chi_{d_1}$ ,  $\chi_{d_2}$  be the associated quadratic Dirichlet characters. Let  $F$  be a cuspidal Siegel eigenform of weight*

$l$  for  $\mathrm{Sp}_4(\mathbb{Z})$  that is not of Saito-Kurokawa type. Then we have

$$L\left(\frac{1}{2}, \pi_{F,f} \times \chi_{d_1}\right) \sim_{\mathbb{Q}(F)} L\left(\frac{1}{2}, \pi_{F,f} \times \chi_{d_2}\right),$$

where " $\sim_{\mathbb{Q}(F)}$ " means up to multiplication by an element in the number field  $\mathbb{Q}(F)$ .

**5.3.6 Remark.** In [4], Böcherer made a remarkable conjecture that expresses the central values  $L\left(\frac{1}{2}, \pi_{F,f} \times \chi_d\right)$ , as  $d$  varies over negative fundamental discriminants, in terms of the Fourier coefficients of  $F$  of discriminant  $d$ . In particular, Böcherer's conjecture implies Corollary 5.3.5 above for the case that  $d_1, d_2$  are both negative. Thus Corollary 5.3.5 can be read as providing evidence towards Böcherer's conjecture.

### Critical value result for $\mathrm{GSp}_4 \times \mathrm{GL}_2$

Next, we provide a critical value result for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$ . This result will not use our lifting theorem, but instead will follow from the integral representation (Theorem 3.6.1) using the methods of [50].

**5.3.7 Theorem.** Let  $F$  be a cuspidal Siegel eigenform of weight  $l$  for  $\mathrm{Sp}_4(\mathbb{Z})$  such that  $F \in S_l(\mathrm{Sp}_4(\mathbb{Z}), \mathbb{Q}(F))$ . Let  $g \in S_l(N, \chi)$  be a primitive Hecke eigenform of level  $N$  and nebentypus  $\chi$ ; here  $N$  is any positive integer, and  $\chi$  a Dirichlet character mod  $N$ . Let  $\pi_F$  and  $\tau_g$  be the irreducible, cuspidal, automorphic representations of  $\mathrm{GSp}_4(\mathbb{A})$  and  $\mathrm{GL}_2(\mathbb{A})$  corresponding to  $F$  and  $g$ . Let  $\mathbb{Q}(F, g, \chi)$  be the field generated by the Hecke eigenvalues of  $F$ , the Hecke eigenvalues of  $g$  and the values taken by  $\chi$ . For a positive integer  $k$ ,  $1 \leq k \leq \frac{\ell}{2} - 2$ , define

$$A(F, g; k) = \frac{L\left(\frac{\ell}{2} - k, F \times g\right)}{\pi^{5\ell-4k-4} \langle F, F \rangle \langle g, g \rangle}.$$

Then we have,

- i)  $A(F, g; k) \in \mathbb{Q}(F, g, \chi)$ ,
- ii) For an automorphism  $\sigma$  of  $\mathbb{C}$ ,  $\sigma(A(F, g; k)) = A(\sigma F, \sigma g; k)$ .

**5.3.8 Remark.** Note that the first claim of the above theorem actually follows from the second.

**5.3.9 Remark.** Partial results towards the above theorem have been previously obtained by Böcherer–Heim [5], Furusawa [15], and various combinations of the authors [43, 45, 49, 50].

**Proof.** The proof is essentially identical to that of Theorem 8.1 of [50] which proved the above result under certain restrictions on  $N$ ,  $\chi$  and  $F$ . More precisely, in [50],  $N$  was assumed to be squarefree and all its prime divisors inert in a certain quadratic field,  $\chi$  was assumed to be trivial, and  $F$  was assumed to satisfy a certain non-vanishing condition on the Fourier coefficients. These restrictions were necessary because the relevant integral representation [50, Thm. 6.4] in that paper was proved only under these assumptions. The special value result in that paper followed from the integral representation by first rewriting the integral representation in classical language and then using results of Garrett and Harris and the theory of nearly holomorphic functions due to Shimura.

However, in the current paper, the second integral representation (Theorem 3.6.1) works for general  $N$  and  $\chi$  and the non-vanishing assumption on  $F$  is always satisfied, as shown in [51]. Now, Theorem 5.3.7 follows in an identical manner as in [50], because the remaining ingredients (the

theory of nearly holomorphic functions and the results of Garrett and Harris) are true for general  $N$  and  $\chi$ . It is worth noting, however, that we still need to assume that the weights of  $F$  and  $g$  are equal (even though the integral representation, Theorem 3.6.1, works for arbitrary  $g$ ) because otherwise the Eisenstein series  $E_Y(g, s)$  at the right-most critical point (corresponding to  $s = \frac{l}{6} - \frac{1}{2}$ ) is no longer holomorphic. ■

## References

- [1] Anatolii Andrianov. Euler products associated with Siegel's modular forms of degree 2. *Russ. Math. Surveys*, 29(3):45–116, 1974.
- [2] Mahdi Asgari and Ralf Schmidt. Siegel modular forms and representations. *Manuscripta Math.*, 104(2):173–200, 2001.
- [3] Mahdi Asgari and Freydoon Shahidi. Generic transfer from  $\mathrm{GSp}(4)$  to  $\mathrm{GL}(4)$ . *Compos. Math.*, 142(3):541–550, 2006.
- [4] Siegfried Böcherer. Bemerkungen über die Dirichletreihen von Koecher und Maass. *Mathematica Gottingensis*, 68:36 pp., 1986.
- [5] Siegfried Böcherer and Bernhard Heim. Critical values of  $L$ -functions on  $\mathrm{GSp}_2 \times \mathrm{GL}_2$ . *Math. Z.*, 254(3):485–503, 2006.
- [6] Daniel Bump. *Automorphic forms and representations*, volume 55 of *Cambridge Studies in Advanced Mathematics*. Cambridge University Press, Cambridge, 1997.
- [7] Daniel Bump and David Ginzburg. Symmetric square  $L$ -functions on  $\mathrm{GL}(r)$ . *Ann. of Math.* (2), 136(1):137–205, 1992.
- [8] William Casselman. On some results of Atkin and Lehner. *Math. Ann.*, 201:301–314, 1973.
- [9] Laurent Clozel. Motifs et formes automorphes: applications du principe de fonctorialité. In *Automorphic forms, Shimura varieties, and  $L$ -functions, Vol. I (Ann Arbor, MI, 1988)*, volume 10 of *Perspect. Math.*, pages 77–159. Academic Press, Boston, MA, 1990.
- [10] James Cogdell and Ilya Piatetski-Shapiro. A converse theorem for  $\mathrm{GL}_4$ . *Math. Res. Lett.*, 3(1):67–76, 1996.
- [11] James Cogdell and Ilya Piatetski-Shapiro. Remarks on Rankin-Selberg convolutions. In *Contributions to automorphic forms, geometry, and number theory*, pages 255–278. Johns Hopkins Univ. Press, Baltimore, MD, 2004.
- [12] Pierre Deligne. Formes modulaires et représentations de  $\mathrm{GL}(2)$ . In *Modular functions of one variable, II (Proc. Internat. Summer School, Univ. Antwerp, Antwerp, 1972)*, pages 55–105. Lecture Notes in Math., Vol. 349. Springer, Berlin, 1973.
- [13] Martin Eichler and Don Zagier. *The theory of Jacobi forms*, volume 55 of *Progress in Mathematics*. Birkhäuser Boston Inc., Boston, MA, 1985.
- [14] William Fulton and Joe Harris. *Representation theory. A first course*, volume 129 of *Graduate Texts in Mathematics*. Springer-Verlag, New York, 1991.

- [15] Masaaki Furusawa. On  $L$ -functions for  $\mathrm{GSp}(4) \times \mathrm{GL}(2)$  and their special values. *J. Reine Angew. Math.*, 438:187–218, 1993.
- [16] Paul Garrett. Pullbacks of Eisenstein series; applications. In *Automorphic forms of several variables (Katata, 1983)*, volume 46 of *Progr. Math.*, pages 114–137. Birkhäuser Boston, Boston, MA, 1984.
- [17] Stephen Gelbart and Erez Lapid. Lower bounds for  $L$ -functions at the edge of the critical strip. *Amer. J. Math.*, 128(3):619–638, 2006.
- [18] Stephen Gelbart and Freydoon Shahidi. Boundedness of automorphic  $L$ -functions in vertical strips. *J. Amer. Math. Soc.*, 14(1):79–107 (electronic), 2001.
- [19] David Ginzburg, Dihua Jiang, and Stephen Rallis. On the nonvanishing of the central value of the Rankin-Selberg  $L$ -functions. *J. Amer. Math. Soc.*, 17(3):679–722 (electronic), 2004.
- [20] David Ginzburg, Stephen Rallis, and David Soudry. Generic automorphic forms on  $\mathrm{SO}(2n+1)$ : functorial lift to  $\mathrm{GL}(2n)$ , endoscopy, and base change. *Internat. Math. Res. Notices*, (14):729–764, 2001.
- [21] I. S. Gradshteyn and I. M. Ryzhik. *Table of integrals, series, and products*. Academic Press [Harcourt Brace Jovanovich Publishers], New York, 1980. Corrected and enlarged edition edited by Alan Jeffrey, Incorporating the fourth edition edited by Yu. V. Geronimus and M. Yu. Tseytlin, Translated from the Russian.
- [22] Valeri Gritsenko. Analytic continuation of symmetric squares. *Math. USSR-Sb.*, (35):593–614, 1979.
- [23] Harald Grobner and A. Raghuram. On the arithmetic of Shalika models and the critical values of  $L$ -functions for  $GL_{2n}$ . *Preprint*, 2011. [arXiv:1106.4249](https://arxiv.org/abs/1106.4249).
- [24] Benedict Gross and Stephen Kudla. Heights and the central critical values of triple product  $L$ -functions. *Compositio Math.*, 81(2):143–209, 1992.
- [25] Michael Harris. Occult period invariants and critical values of the degree four  $L$ -function of  $\mathrm{GSp}(4)$ . In *Contributions to automorphic forms, geometry, and number theory*, pages 331–354. Johns Hopkins Univ. Press, Baltimore, MD, 2004.
- [26] Atsushi Ichino. A regularized Siegel-Weil formula for unitary groups. *Math. Z.*, 247(2):241–277, 2004.
- [27] Hervé Jacquet. *Automorphic forms on  $\mathrm{GL}(2)$ . Part II*. Lecture Notes in Mathematics, Vol. 278. Springer-Verlag, Berlin, 1972.
- [28] Hervé Jacquet and Joseph Shalika. On Euler products and the classification of automorphic representations. I. *Amer. J. Math.*, 103(3):499–558, 1981.
- [29] Henry Kim. Functoriality for the exterior square of  $\mathrm{GL}_4$  and the symmetric fourth of  $\mathrm{GL}_2$ . *J. Amer. Math. Soc.*, 16(1):139–183 (electronic), 2003. With appendix 1 by Dinakar Ramakrishnan and appendix 2 by Henry Kim and Peter Sarnak.
- [30] Alois Krieg and Martin Raum. The functional equation for the twisted spinor  $L$ -function of genus 2. *Preprint*, 2009. [arXiv:0907.2767](https://arxiv.org/abs/0907.2767).

- [31] Stephen Kudla. Seesaw dual reductive pairs. In *Automorphic forms of several variables (Katata, 1983)*, volume 46 of *Progr. Math.*, pages 244–268. Birkhäuser Boston, Boston, MA, 1984.
- [32] Stephen Kudla and Stephen Rallis. A regularized Siegel-Weil formula: the first term identity. *Ann. of Math. (2)*, 140(1):1–80, 1994.
- [33] Stephen Kudla, Stephen Rallis, and David Soudry. On the degree 5  $L$ -function for  $\mathrm{Sp}(2)$ . *Invent. Math.*, 107(3):483–541, 1992.
- [34] Stephen Kudla and Jay Sweet. Degenerate principal series representations for  $\mathrm{U}(n, n)$ . *Israel J. Math.*, 98:253–306, 1997.
- [35] Nobushige Kurokawa. On Siegel eigenforms. *Proc. Japan Acad. Ser. A Math. Sci.*, 57(1):47–50, 1981.
- [36] Robert Langlands. *Euler products*. Yale University Press, New Haven, Conn., 1971. A James K. Whittemore Lecture in Mathematics given at Yale University, 1967, Yale Mathematical Monographs, 1.
- [37] Erez Lapid. On the nonnegativity of Rankin-Selberg  $L$ -functions at the center of symmetry. *Int. Math. Res. Not.*, (2):65–75, 2003.
- [38] Soo Teck Lee and Chen-Bo Zhu. Degenerate principal series and local theta correspondence. *Trans. Amer. Math. Soc.*, 350(12):5017–5046, 1998.
- [39] Wilhelm Magnus, Fritz Oberhettinger, and Raj Pal Soni. *Formulas and theorems for the special functions of mathematical physics*. Third enlarged edition. Die Grundlehren der mathematischen Wissenschaften, Band 52. Springer-Verlag New York, Inc., New York, 1966.
- [40] Shin-ichiro Mizumoto. Poles and residues of standard  $L$ -functions attached to Siegel modular forms. *Math. Ann.*, 289(4):589–612, 1991.
- [41] Hiroaki Narita, Ameya Pitale, and Ralf Schmidt. Irreducibility criteria for local and global representations. *Preprint*, 2011. [arXiv:1105.5169](https://arxiv.org/abs/1105.5169).
- [42] Ilya Piatetski-Shapiro. On the Saito-Kurokawa lifting. *Invent. Math.*, 71(2):309–338, 1983.
- [43] Ameya Pitale. Steinberg representation of  $\mathrm{GSp}(4)$ : Bessel models and integral representation of  $L$ -functions. *Pac. J. Math.*, 250(2):365–406, 2011.
- [44] Ameya Pitale and Ralf Schmidt. Bessel models for lowest weight representations of  $\mathrm{GSp}(4, \mathbb{R})$ . *Int. Math. Res. Not. IMRN*, (7):1159–1212, 2009.
- [45] Ameya Pitale and Ralf Schmidt. Integral representation for  $L$ -functions for  $\mathrm{GSp}_4 \times \mathrm{GL}_2$ . *J. Number Theory*, 129(6):1272–1324, 2009.
- [46] Ameya Pitale and Ralf Schmidt. Ramanujan-type results for Siegel cusp forms of degree 2. *J. Ramanujan Math. Soc.*, 24(1):87–111, 2009.
- [47] Tomasz Przebinda. The oscillator duality correspondence for the pair  $\mathrm{O}(2, 2)$ ,  $\mathrm{Sp}(2, \mathbf{R})$ . *Mem. Amer. Math. Soc.*, 79(403):x+105, 1989.

- [48] Brooks Roberts and Ralf Schmidt. *Local newforms for  $\mathrm{GSp}(4)$* , volume 1918 of *Lecture Notes in Mathematics*. Springer, Berlin, 2007.
- [49] Abhishek Saha.  $L$ -functions for holomorphic forms on  $\mathrm{GSp}(4) \times \mathrm{GL}(2)$  and their special values. *Int. Math. Res. Not. IMRN*, (10):1773–1837, 2009.
- [50] Abhishek Saha. Pullbacks of Eisenstein series from  $\mathrm{GU}(3, 3)$  and critical  $L$ -values for  $\mathrm{GSp}(4) \times \mathrm{GL}(2)$ . *Pacific J. Math.*, 246(2):435–486, 2010.
- [51] Abhishek Saha. Siegel cusp forms of degree 2 are determined by their fundamental Fourier coefficients. *Preprint*, 2011. [arXiv:1106.5110](https://arxiv.org/abs/1106.5110).
- [52] Paul Sally, Jr. and Marko Tadić. Induced representations and classifications for  $\mathrm{GSp}(2, F)$  and  $\mathrm{Sp}(2, F)$ . *Mém. Soc. Math. France (N.S.)*, (52):75–133, 1993.
- [53] Ralf Schmidt. Some remarks on local newforms for  $\mathrm{GL}(2)$ . *J. Ramanujan Math. Soc.*, 17(2):115–147, 2002.
- [54] Freydoon Shahidi. On certain  $L$ -functions. *Amer. J. Math.*, 103(2):297–355, 1981.
- [55] Freydoon Shahidi. On the Ramanujan conjecture and finiteness of poles for certain  $L$ -functions. *Ann. of Math. (2)*, 127(3):547–584, 1988.
- [56] Goro Shimura. On the Fourier coefficients of modular forms of several variables. *Nachr. Akad. Wiss. Göttingen Math.-Phys. Kl. II*, (17):261–268, 1975.
- [57] Goro Shimura. *Euler products and Eisenstein series*, volume 93 of *CBMS Regional Conference Series in Mathematics*. Published for the Conference Board of the Mathematical Sciences, Washington, DC, 1997.
- [58] Takashi Sugano. On holomorphic cusp forms on quaternion unitary groups of degree 2. *J. Fac. Sci. Univ. Tokyo Sect. IA Math.*, 31(3):521–568, 1985.
- [59] Victor Tan. A regularized Siegel-Weil formula on  $\mathrm{U}(2, 2)$  and  $\mathrm{U}(3)$ . *Duke Math. J.*, 94(2):341–378, 1998.
- [60] Victor Tan. Poles of Siegel Eisenstein series on  $\mathrm{U}(n, n)$ . *Canad. J. Math.*, 51(1):164–175, 1999.
- [61] John Tate. Fourier analysis in number fields, and Hecke’s zeta-functions. In *Algebraic Number Theory (Proc. Instructional Conf., Brighton, 1965)*, pages 305–347. Thompson, Washington, D.C., 1967.
- [62] John Tate. Number theoretic background. In *Automorphic forms, representations and  $L$ -functions (Proc. Sympos. Pure Math., Oregon State Univ., Corvallis, Ore., 1977), Part 2*, Proc. Sympos. Pure Math., XXXIII, pages 3–26. Amer. Math. Soc., Providence, R.I., 1979.
- [63] Jean-Loup Waldspurger. Quelques propriétés arithmétiques de certaines formes automorphes sur  $\mathrm{GL}(2)$ . *Compositio Math.*, 54(2):121–171, 1985.
- [64] Rainer Weissauer. Existence of Whittaker models related to four dimensional symplectic Galois representations. In *Modular forms on Schiermonnikoog*, pages 285–310. Cambridge Univ. Press, Cambridge, 2008.
- [65] Rainer Weissauer. *Endoscopy for  $\mathrm{GSp}(4)$  and the cohomology of Siegel modular threefolds*, volume 1968 of *Lecture Notes in Mathematics*. Springer-Verlag, Berlin, 2009.